

The Influence of Storm Size on Hurricane Surge

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ABSTRACT

Over the last quarter-century, hurricane surge has been assumed to be primarily a function of maximum storm wind speed, as might be estimated from the Saffir–Simpson hurricane scale. However, Hurricane Katrina demonstrated that wind speed alone cannot reliably describe surge. Herein it is shown that storm size plays an important role in surge generation, particularly for very intense storms making landfall in mildly sloping regions. Prior to Hurricane Katrina, analysis of the historical hurricane record evidenced no clear correlation between surge and storm size, and consequently little attention was given to the role of size in surge generation. In contrast, it is found herein that, for a given intensity, surge varies by as much as 30% over a reasonable range of storm sizes. These findings demonstrate that storm size must be considered when estimating surge, particularly when predicting socioeconomic and flood risk.

1. Introduction

The Saffir–Simpson hurricane scale (Table 1) was developed in 1969 to provide weather forecasters and emergency planners with a simple method for estimating wind damage potential (e.g., Simpson 1974). This scale is based solely on estimated maximum wind speed within a hurricane, and in spite of its narrow perspective, has proven to be an adequate indicator of hurricane wind damage. However, reliance on this scale as an indicator of potential storm surge has led to serious misconceptions within the public and scientific communities alike. For example, the Saffir–Simpson scale cannot be used to answer why a storm like Hurricane Katrina, classified by the National Oceanographic and Atmospheric Administration (NOAA) as a category 3 storm at landfall (National Weather Service 2005; Blake et al. 2006), produced a much larger storm surge

than that produced by Hurricane Camille, classified by NOAA as a category 5 storm at landfall (Blake et al. 2006; Neumann et al. 1999). As will be shown here, the primary reason for this discrepancy appears to be in storm size. The purpose of this paper is to investigate the general influence of hurricane size, in addition to wind speed (Saffir–Simpson scale), in generating surge at the coast.

As noted in an article on the rising death toll in Hurricane Katrina found in Biloxi, Mississippi's *Sun Herald* (Norman 2006), "an oft heard refrain . . . is Hurricane Camille killed more people in 2005 than it did in 1969. Many officials and locals believed those . . . who had survived what was then the strongest recorded hurricane were lulled into a false sense of security that kept them in harm's way." Even today, many people still echo the sentiment that it would have been much worse if a Saffir–Simpson category 5 storm had struck this area rather than Katrina. Evidence will be presented that shows the Saffir–Simpson scale is not a particularly good indicator of storm surge along the coast and that storm size, along with bottom slope, is also a critical factor in the generation of large coastal surges.

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TABLE 1. Saffir–Simpson hurricane scale (Simpson 1974; National Weather Service 2006).

Saffir–Simpson category	Max 1-min wind speed (m s^{-1})	Storm surge (m)
1	33.0–42.5	1.2–1.5
2	42.9–49.2	1.8–2.4
3	49.6–58.1	2.7–3.7
4	58.6–69.3	4.0–5.5
5	>69.3	>5.5

Figure 1 shows a measure of storm intensity (far-field pressure, estimated as 1020 mb, less central pressure Δp) and a measure of size (radius to maximum wind speed R_{max}) for Hurricanes Camille (left side) and Katrina (right side) as a function of distance to landfall. As this figure shows, Hurricane Katrina was significantly larger than Hurricane Camille during its entire passage through the Gulf of Mexico, as well as during its final approach to land. In this paper we will examine the hypothesis that storm size significantly influences the potential for storm surge generation in hurricanes. As will be shown here, it is very likely that storm size is the dominant factor in surge generation for these two storms, and that this is the primary reason why surges in Hurricane Katrina [7.5–8.5 m; see U.S. Army Corps of Engineers (2006a)] were substantially higher than surges in Hurricane Camille [6.4–6.9 m; see U.S. Army Corps of Engineers (2006b)]. Furthermore, it appears that on all shallow coasts, the role of storm size in surge generation can be of the same magnitude as storm intensity, particularly for intense storms.

In this paper we will first provide a background on past efforts to characterize hurricane surge and an overview of hurricane surge generation. Next, we detail our approach for investigating the surge response to hurricane size, in addition to wind speed and continental shelf slope. Finally, we present our results and analyses with respect to historical observations.

2. Background

To appreciate the lack of focus on hurricane size and the emphasis on the Saffir–Simpson scale as an indicator of hurricane surge, it is useful to examine the history of storm surge response research. Earlier studies to correlate peak storm surge with hurricane meteorological conditions suggested that storm size is not well correlated with peak surge, and that the Saffir–Simpson scale may be a reasonable surge indicator by area (Hoover 1957; Conner et al. 1957; Harris 1959, 1963; Jelesnianski 1972). Building on initial analyses (Hoover 1957; Conner et al. 1957), Harris (1959, 1963) stated that peak

surge was determined by a simple relationship to the central pressure and regional bottom slope. Jelesnianski (1972) used a numerical hydrodynamic model to develop a series of nomographs relating peak surge to central pressure, storm size, and a shoaling factor. Although accounting for storm size, he noted that peak surge was only weakly dependent on size.

Since the 1970s, the scientific and public communities alike have accepted that peak surge may largely be determined from either the central pressure deficit or the related maximum wind speed (Saffir–Simpson scale). Consequently, most hurricane surge studies, for both forecasting and coastal protection design, have relied heavily on intensity and wind speed as the determining factors for hurricane surge response (e.g., Berke et al. 1984). While both hurricane intensity and size are regularly included, along with local geometry, when simulating and predicting hurricane surge with the Sea, Lake, and Overland Surges from Hurricanes (SLOSH; Jelesnianski 1984, 1990) and other models (e.g., Westerink et al. 2007), the resulting surge from these prediction models has traditionally been attributed to intensity and presented with respect to the Saffir–Simpson category. Blain et al. (1998) did investigate storm size, but only in the context of optimizing grid resolution for numerical surge simulation. Most methods to characterize surge in the Atlantic and Gulf of Mexico, while considering storm size, have followed the earlier works reported in the 1950s through the 1970s and have not analyzed a large enough hurricane size range, particularly in conjunction with very shallow continental shelves, to fully capture the impact of hurricane size on surge generation (e.g., Taylor 1980; Russo 1998; Weisberg and Zheng 2006).

In the early 1990s, Dolan and Davis (1992) and Davis and Dolan (1993) recognized the shortcomings of the Saffir–Simpson scale for predicting storm damage, and they presented an intensity scale that additionally correlates storm duration and wave power for extratropical storm events with coastal erosion and overwash. However, this intensity scale, which was developed for very large weather systems, does not give an indication of expected peak storm surge as it relates to storm size. Almost all hurricane flood damage studies show that damage to communities along the Gulf of Mexico are primarily a function of flood elevation. For example, the extensive surveys conducted following Hurricane Katrina did not show a high correlation between flooding duration and damage, but they did demonstrate a high correlation between flood elevation and damage.

Weisberg and Zheng (2006) studied the influence of the Saffir–Simpson scale (hurricane intensity), landfall location, forward speed, and direction with respect to

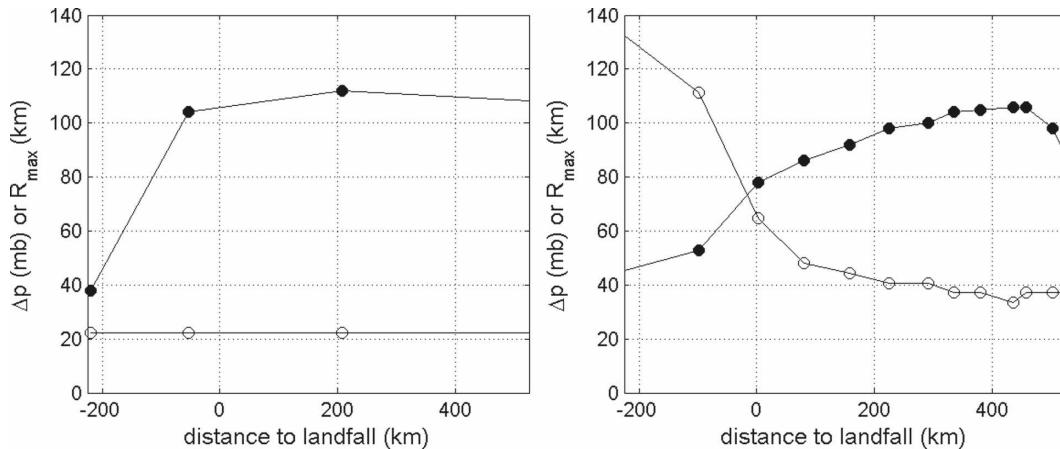


FIG. 1. Observed hurricane intensity (Δp , solid) and size (R_{max} , hollow) as Hurricanes (left) Camille and (right) Katrina move landward. Hurricanes track from right to left such that distances prior to landfall are positive.

the coast on simulated hurricane surge within a bay and concluded that the surge response was indeed sensitive to all of these parameters. While Weisberg and Zheng (2006) considered two different hurricane sizes in their analysis, only one size per Saffir–Simpson category was investigated; thus, no conclusions could be drawn in regard to the influence of hurricane size on surge for a given storm intensity.

Most recently, Powell and Reinhold (2007) presented a new approach for assessing wind damage by hurricanes by considering the integrated kinetic energy over the entire storm, thus inherently including storm size, rather than solely relying on maximum wind speed. However, such an approach has yet to be considered for hurricane surge estimation.

The above-mentioned hurricane studies emphasized storm intensity with limited consideration of storm size. The specific influence of hurricane size on storm surge has not yet been characterized largely because the influence of storm size has historically been considered insignificant, based upon those studies performed in the late 1950s through the early 1970s, which could not make use of data on very large hurricanes like Hurricane Katrina. However, the limited consideration given to hurricane size has led to widespread misconceptions regarding surge generation by hurricanes, and in particular by Hurricane Katrina. In this paper, we seek to address this shortcoming in the state of knowledge regarding hurricane surge generation.

To newly investigate the role of storm size on hurricane surge potential, it is essential to appropriately represent the hurricane wind field and to use a high-quality numerical model, such as the Advanced Circulation (ADCIRC) model, for hurricane surge generation. The following gives a conceptual overview of hurricane

wind field structure and hurricane surge generation. Although it is recognized that hurricanes can have very complex wind field structures (e.g., double eyewalls, eyewall replacement cycles, organized spiral bands, asymmetries resulting from proximity to land, etc.), a simple set of parameters has proven effective for estimating winds within hurricanes for the purpose of driving ocean response models (Thompson and Cardone 1996; Vickery et al. 2000). Primary parameters used in this context typically include

- 1) central pressure deficit as a measure of storm intensity,
- 2) a radius scale related to storm size,
- 3) the forward speed of the storm, and
- 4) the peakedness of the storm wind speed distribution (Holland’s B ; see Holland 1980).

Direct wind stress, wave radiation stresses, and barotropic water level adjustments represent the primary surge forcing mechanisms within a hurricane. In this paper, we neglect the effects of waves to simplify our analyses. The justification for this is twofold. First, this paper is not intended to improve the precise calculation of storm surge, but rather to isolate the effect of storm size on coastal surge levels. Second, because the size of a hurricane affects both the fetch and duration for generating waves, increasing storm size tends to increase wave heights, which would lead to higher wave setup along the coasts. Including this effect would, if anything, add to the hypothesized positive relationship between increasing storm size and coastal surges. Contributions to storm surge resulting from astronomical tide are also neglected in this paper, because these contributions are largely independent of hurricane size.

For the case of steady onshore wind acting uniformly on a water body with constant bottom slope (S_o), the storm surge (ζ) is of the form

$$\zeta \propto \frac{\tau}{S_o} \propto \frac{V^2}{S_o}, \quad (1)$$

where τ is the wind shear stress at the water surface and V is wind speed. In the more realistic case of space–time-varying hurricane wind fields, both storm size and its forward speed affect the duration of high winds at a given point. Close to the hurricane’s center, the cyclostrophic approximation for wind speed [$V(r)$] as a function of distance from the storm eye (r), in the absence of storm forward motion, is given by (Holland 1980)

$$V(r) = \left[\left(\frac{r}{R_{\max}} \right)^B \left(\frac{B\Delta p}{\rho_{\text{air}}} \right) e^{-\left(\frac{R_{\max}}{r} \right)^B} \right]^{1/2}, \quad (2)$$

where B is Holland’s dimensionless parameter that dictates the radial pressure profile shape and typically ranges from 0.9 to 1.9. Evaluating Eq. (2) at the point of maximum wind demonstrates that maximum wind speed is directly proportional to the square root of Δp , thus illustrating the well-accepted view that Δp is the primary scaling factor for the storm wind field, and thus storm surge. However, Eq. (2) also demonstrates that the radial size of the storm is important when considering the spatial distribution of hurricane winds, and suggests that storm size must also contribute to storm surge generation.

In nature, the cyclonic wind field distribution is modified by several factors. As the storm approaches the coast, the hurricane track angle relative to the coast and the hurricane forward speed both strongly influence the progression of the wind directions. Thus, in the more general case, storm intensity, size, track, and forward speed, and bottom slope are all expected to influence coastal hurricane surges. Other factors affecting total surge at the shoreline include attributes of the coastal landscape, such as the configuration of the land–sea interface, the bottom roughness in offshore and inundated areas, and the relative phase of astronomical tide and hurricane landfall. The influence of specific historical hurricanes on specific coastal landscapes along the Gulf of Mexico has been well studied by a number of investigators (e.g., Westerink et al. 2007; Signorini et al. 1992; Luettich et al. 1992; Westerink et al. 1992). It is our intent here to simplify the storm surge problem to more generally assess the influence and interaction of meteorological parameters like storm size with regional-scale topography, namely, continental shelf slope.

3. Approach

To investigate the influence of storm size on peak storm surge, a numerical investigation of idealized hurricanes was conducted. The assumptions made in our analysis are fairly simple, and we have done this on purpose to isolate surge scaling with storm size. Central pressure deficit, storm size, storm forward speed, and peakedness, in conjunction with information on the background pressure field, were used as input into a coupled hurricane vortex–planetary boundary layer (PBL) model (Thompson and Cardone 1996) to estimate sustained near-surface winds throughout the storm.

Storm wind and pressure fields were generated using the PBL model for 18 unique R_{\max} and Δp pairs by incrementally varying R_{\max} from 18.5 to 55.6 km, and Δp from 40 to 130 mb. For each field, the R_{\max} and Δp values were held constant as the storm progressed due northward with a speed of 5.1 m s^{-1} . Additional wind and barometric pressure fields with alternate track angles and forward speeds were also generated to assess surge generation sensitivity to these parameters. In addition to this base set of simulations, a series of sensitivity simulations were carried out to assess the impact on peak surge by hurricane track variation (60° to the west through 45° to the east of due north) and forward speed (2.6 – 10.3 m s^{-1}).

Using the PBL-modeled wind fields, storm surges along the shoreline were computed from the finite-element longwave ADCIRC numerical model (Westerink et al. 1992; Luettich et al. 1992), with the coefficient of wind drag within the ADCIRC model “capped” to follow measured wind drag relationships (Powell et al. 2003).

For this experiment, the ADCIRC model domain included the entire Gulf of Mexico water body, with simplifications. In particular, the northern gulf boundary was represented by a straight coastline with an east–west orientation. The regional bathymetry within the model grid was further simplified by using shore-parallel contours with a constant bottom slope. Using this grid configuration, storm surge simulations were performed for eight different bottom slopes S_o , ranging from 1:10 000 to 1:250. These slopes represent very mild to very steep idealized continental shelf regions, with the mildest slope representative of conditions in the vicinity of New Orleans, Louisiana.

4. Numerical simulations

To quantify the influence of storm size on surge, peak storm surge for each storm and slope combination was

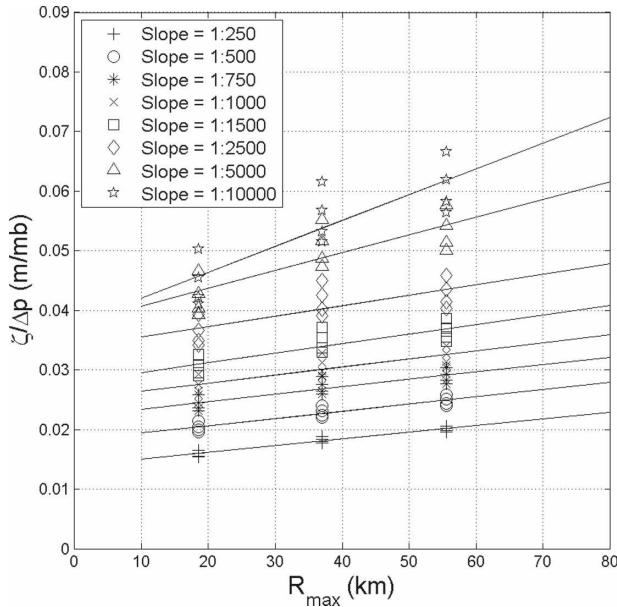


FIG. 2. Simulated hurricane surge (ζ) normalized by central pressure deficit (Δp) vs hurricane size (R_{\max}) at landfall.

extracted from the ADCIRC simulation results. Figure 2 shows the relationship between peak surge at the coast and storm size for moderately intense to very intense storms ($\Delta p \geq 80$ mb). In this figure, the effect of hurricane intensity is removed from this comparison by dividing peak surge by intensity, where intensity is proportional to the square of the maximum wind speed, which translates to the Saffir–Simpson category [Eq. (2)]. As this figure demonstrates, for a given shelf slope the peak surge increases as storm size increases, indicating that storm size effectively increases the distance over which the wind acts. Furthermore, because the linear trend with storm size becomes steeper as shelf slope becomes milder, this figure also shows that the role of storm size in producing surge becomes increasingly important over mildly sloping bottoms. This trend with hurricane size or slope is not captured by the Saffir–Simpson scale.

Figure 3 shows that for bottom slopes of 1:1,000 and 1:10,000, peak storm surge increases as expected with increasing Δp and with decreasing bottom slope. Yet this figure also shows that peak surge depends not only on storm intensity, but also on storm size. When $S_o = 1:1000$ and $\Delta p = 100$ mb, peak surge at the shoreline varies from 2.8 to 3.3 m as R_{\max} varies from 18.5 to 55.6 km. This surge variation is much greater for the very mildly sloping case of $S_o = 1:10,000$, where peak surge at the shoreline varies from 4.5 to 6.2 m.

To assess the sensitivity of storm surge to storm track, additional numerical simulations were performed

by varying the angle of storm approach, while holding storm forward speed constant at 5.1 m s^{-1} . As expected, all storm tracks with more westerly headings (positive angles) produced smaller surges than the due north track for both moderately and mildly sloping bottoms (Fig. 4). For the most mildly sloping bottom, those storms with a more easterly heading (negative angles) produced surges that were as large, or slightly larger (no more than 8%), than the due north track. Other tracks tend to reduce the storm surge, with a maximum reduction of approximately 25%. These simulations indicate that consideration of tracks perpendicular to the shoreline tend to overpredict peak surge produced by more oblique approach angles, on average by 8%.

Next, a series of simulations were performed by varying storm forward speed from 2.6 to 10.2 m s^{-1} to assess sensitivity to this parameter. The simulation results indicate a correlation between storm forward speed and peak storm surge for steep to moderate bottom slopes, primarily because the PBL model produces higher maximum wind speeds within faster-moving storms than slower storms (Fig. 5). When $S_o \leq 1:2500$, a 50% increase in forward speed translates to a 15%–20% increase in peak surge. For more mildly sloping bottoms, only a minimal increase, if any, in the peak surge was predicted. This limited surge response predicted by the simulations on mildly sloping bottoms, like those near New Orleans, arises because the relative decrease in storm residence time offshore with increased storm forward speed dominates the surge response. Here, an equilibrium state is approached more quickly, even for fast-moving storms, because the mild slope creates a much larger shallow area (e.g., increased fetch) over which the hurricane winds act. On more steeply sloping bottoms the effective cross-shore area over which the winds act is smaller and thus less influential; therefore, the relative increase in hurricane wind speed with increasing forward speed dominates the simulated surge response.

5. Results

As was seen in Fig. 3, the numerical results indicate that, in addition to storm intensity and bottom slope, storm size is important in generating surge at the coast. For a given storm intensity, the figure plainly shows that simulated storm surge increases with storm size, and that this relationship holds for all bottom slopes. However, the numerical results indicate that the role of storm size in surge generation becomes much more important on mildly sloping bottoms and for intense storms. For example, given a value of Δp equal to 70 mb on a slope of 1:10,000, peak surge increases 0.4 m for

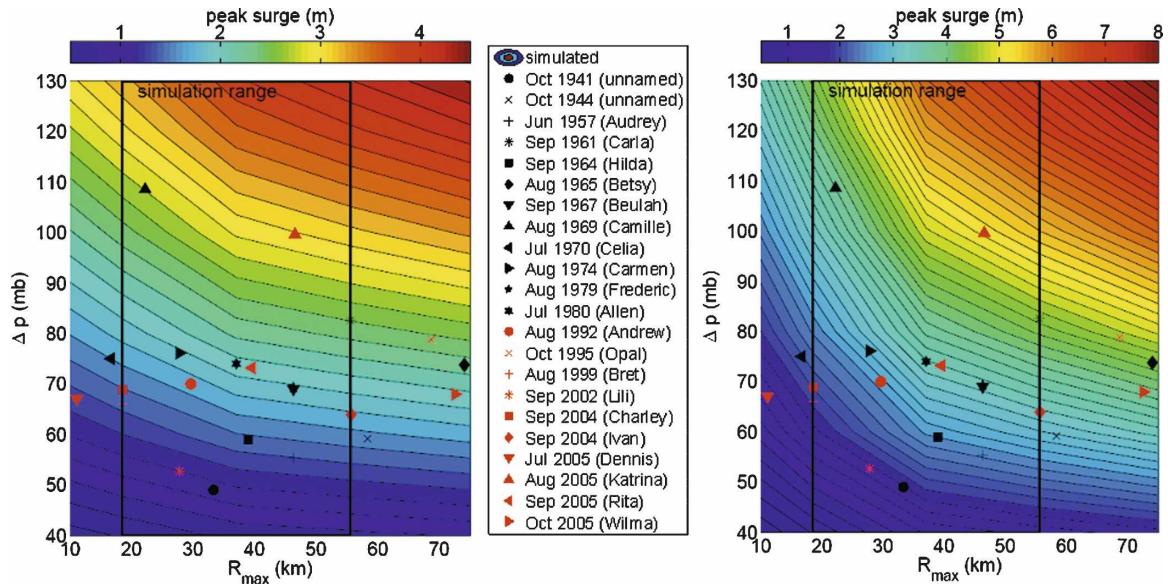


FIG. 3. Simulated peak surge as a function of hurricane size (R_{max}) and intensity (Δp) for the (left) 1:1000 bottom slope (S_o) case and the (right) 1:10 000 bottom slope (S_o) case. Historical R_{max} and Δp observations are superimposed on the numerical results to indicate peak surge potential if the historical storm made landfall in a region characterized by a bottom slope of either (a) 1:1000 or (b) 1:10 000.

every 10-km increase in R_{max} . The same storm on a 1:1000 slope produces only an increase of 0.15 m for every 10-km increase in R_{max} . Likewise, a horizontal cut through Fig. 3 at large values of Δp shows a much higher variability in surge levels than a cut at small values of Δp . Because older studies of storm surge primarily dealt with surges from moderate storms on moderate slopes (Hoover 1957; Conner et al. 1957; Harris

1959, 1963; Jelesnianski 1972), it is not too surprising that no strong relationship between storm size and peak surge at the coast was found.

Historical observations may also be used to support the contention that storm size is more important for surge generation on mildly sloping bottoms and for more intense hurricanes. Figure 6 shows observed peak surge versus storm size at landfall for the subset of

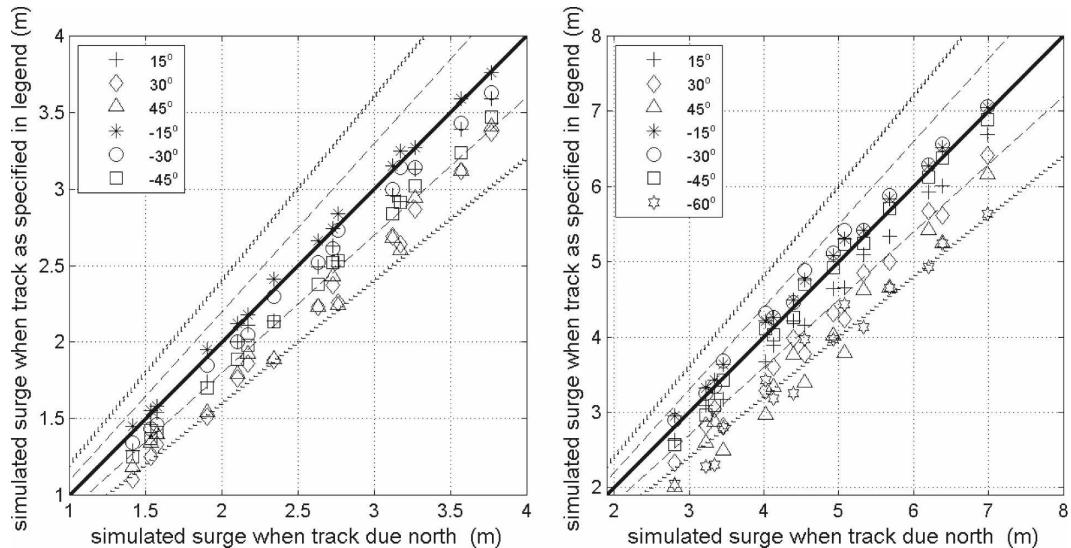


FIG. 4. Simulated peak surge as a function of hurricane track angle, measured counterclockwise from a due north approach for (left) $S_o = 1:1000$ and (right) $S_o = 1:10\ 000$. Plus or minus 0%, 10%, and 20% increases or decreases in value are marked by the solid, dashed, and dotted lines, respectively.

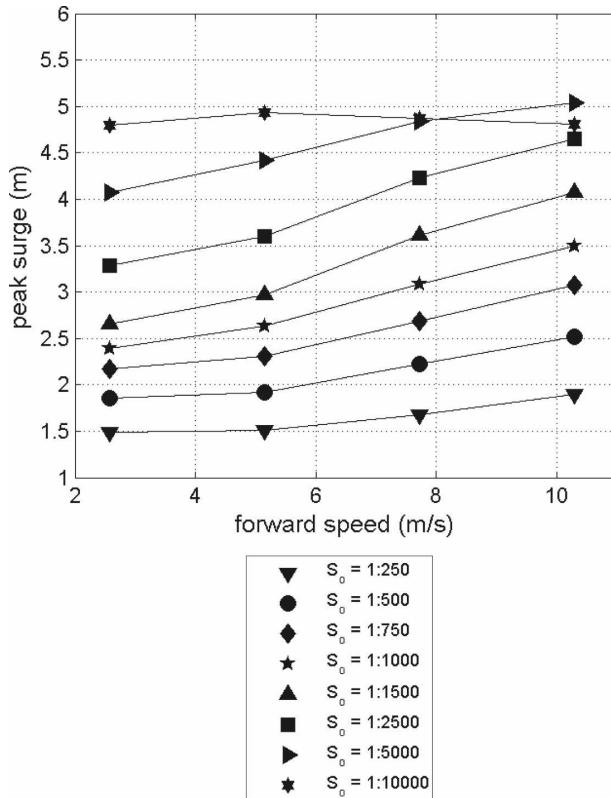


FIG. 5. Simulated peak surge as a function of storm forward speed and bottom slope.

historical hurricanes with intensities greater than $\Delta p = 80$ mb. As in Fig. 2, the effect of hurricane intensity is removed from the comparison presented in Fig. 6 by dividing peak surge by intensity, which correlates with the Saffir–Simpson category. Figure 6 demonstrates that the observed data support the numerical findings presented in Fig. 2. Specifically, Fig. 6 shows evidence that increases in storm size increase storm surge and that this relationship becomes more significant as shelf slope becomes milder. This figure and our numerical findings both support our claim that the Saffir–Simpson scale alone is not a good indicator of peak hurricane surge.

Superimposed on Fig. 3 are the Δp and R_{max} values at landfall for 22 major hurricanes (Table 2). On the figure, the R_{max} and Δp combination for Hurricane Katrina plots at a higher peak surge level than that for Hurricane Camille. When $S_o = 1:1000$, the R_{max} and Δp combination for Hurricane Betsy, also a major hurricane impacting the Mississippi and Louisiana coastlines, plots at a slightly lower peak surge level than that for Hurricane Camille. Illustrating the importance of bottom slope on surge prediction for the more mildly sloping $S_o = 1:10\,000$ case, peak surge values for these

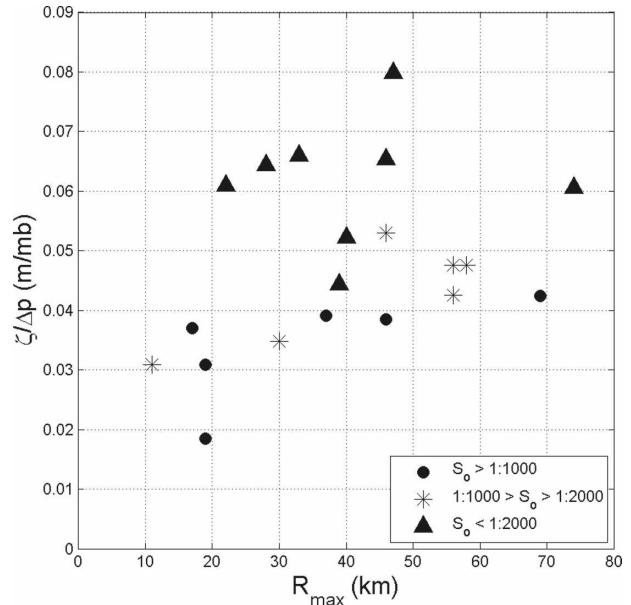


FIG. 6. Observed hurricane surge (ζ) normalized by observed central pressure deficit (Δp) vs hurricane size (R_{max}) at landfall.

two storms are reversed, with Hurricane Betsy associated with a slightly larger surge than Hurricane Camille. The actual slope along the coastline near New Orleans falls between the 1:1000 and 1:10 000 slope values, so these significantly different storms impacting New Orleans produce similar peak surges in our simulations.

Using the numerical results and following curve-fitting procedures, a parametric relationship between peak surge at the shoreline and Δp , R_{max} , and S_o was developed (see the appendix). Figure 7 plots this peak surge estimate versus the observed peak surge. While the relationship developed from the idealized simulations does not include wave setup, which is significant for most storms, astronomical tide, and impacts of local geometry, the observations match reasonably well. In particular, estimates for hurricanes of moderate intensity and size largely fall below the observed value by 10%–20%. Because wave setup was not included in the numerical analysis, it is logical that the estimate based on the numerical results is low. Furthermore, it is probable that wave setup contributes on the order of 10%–20% to the total hurricane water level along Gulf of Mexico coastlines (Dean and Bender 2006; U.S. Army Corps of Engineers 2006a).

The results for Hurricanes Ivan, Dennis, and Frederic, whose central pressure deficit were within 5 mb of one another, demonstrate that the surge estimates capture the relative influence of storm size on moderately sloping bottoms. Hurricanes Ivan and Dennis

TABLE 2. Historical hurricane characteristics at landfall.

Storm date (Name)	Central pressure (mb) ^a	Radius to maximum wind (km) ^b	Saffir–Simpson category ^c	Estimated influencing continental shelf slope	Observed open coast surge (m)
October 1941 (unnamed)	970	33	2	1:2,000–1:3,500	3.2 ^d
October 1944 (unnamed)	960	58	3	1:1,500–1:1,700	2.3–3.4 ^d
June 1957 (Audrey)	964	46	4	1:4,000	3.4–3.8 ^d
September 1961 (Carla)	936	56	4	1:1,000–1:1,700	3.3–3.7 ^e
September 1964 (Hilda)	960	39	3	1:4,000–1:7,500	2.3–3.0 ^f
August 1965 (Betsy)	945	74	3	1:5,000–1:10,000	4.1–4.8 ^f
September 1967 (Beulah)	950	46	3	1:800–1:1,100	2.4–2.9 ^g
August 1969 (Camille)	910	22	5	1:5,000–1:10,000	6.4–6.9 ^f
July 1970 (Celia)	944	17	3	1:800–1:1,100	2.7–2.8 ^h
August 1974 (Carmen)	943	28	3	1:2,500	
August 1979 (Frederic)	950	46	3	1:1,500–1:1,900	3.5–3.8 ⁱ
July 1980 (Allen)	945	37	3	1:800–1:1,100	2.1–3.7 ^h
August 1992 (Andrew)	949	30	5	1:750–1:1,500	2.4 ^j
October 1995 (Opal)	940	69	3	1:750–1:1,000	3.1–3.7 ^k
August 1999 (Bret)	953	19	3	1:800–1:1,100	0.9–1.5 ^l
September 2002 (Lili)	966	28	1	1:4,000–1:7,500	3.2–3.6 ^f
September 2004 (Charley)	950	19	4	1:500–1:1,000	2.1
September 2004 (Ivan)	955	56	3	1:1,500–1:1,900	3.0–3.1 ^m
July 2005 (Dennis)	952	11	3	1:750–1:1,500	1.7–2.5 ⁿ
August 2005 (Katrina)	919	47	3	1:5,000–1:10,000	7.5–8.5 ^b
September 2005 (Rita)	946	40	3	1:2,500–1:3,000	3.0–4.6 ^o
October 2005 (Wilma)	951	73	3	1:500–1:1,000	1.8–2.4 ^p

^a National Weather Service (2000)

^b U.S. Army Corps of Engineers (2006a)

^c Blake et al. (2006)

^d Harris (1963)

^e Ho and Miller (1982)

^f U.S. Army Corps of Engineers (2006b)

^g U.S. Army Corps of Engineers (1968)

^h National Weather Service (2000)

ⁱ U.S. Army Corps of Engineers (1981)

^j National Weather Service (1993)

^k U.S. Army Corps of Engineers (1995)

^l Lawrence and Kimberlain (2001)

^m National Weather Service (2005)

ⁿ National Oceanic and Atmospheric Administration (2005)

^o Knabb et al. (2006)

^p Pasch et al. (2006)

both made landfall along the Alabama coastline, while Hurricane Frederic made landfall slightly to the east, along the western Florida Panhandle. Hurricanes Ivan and Frederic were large in size while Hurricane Dennis was the smallest in the considered historic record. Consequently, the observations and the surge estimate for Hurricane Dennis are about 1 m lower than those for Hurricanes Ivan and Frederic.

The three largest storms, in terms of peak surge, are Hurricanes Betsy, Camille, and Katrina, all making landfall in the vicinity of New Orleans. These three storms demonstrated that the surge estimates do also capture the relative influence of storm size and storm intensity on mildly sloping bottoms. A larger surge is

estimated for Hurricane Katrina than for Hurricane Camille, which was a more intense but much smaller storm. Additionally, the surge estimate for Hurricane Betsy is smaller than that estimated for both Hurricanes Katrina and Camille, largely reflecting Betsy's significantly weaker intensity. However, it is interesting to note that Hurricane Betsy, both in terms of observed and estimated surge, generated the third largest surge of historical storms considered; thus, this storm demonstrates that the surge estimates also capture the influence of hurricane size, for which Betsy is the largest in the historical set, for weak storms passing over a mild continental shelf slope.

However, for both Hurricanes Katrina and Camille,

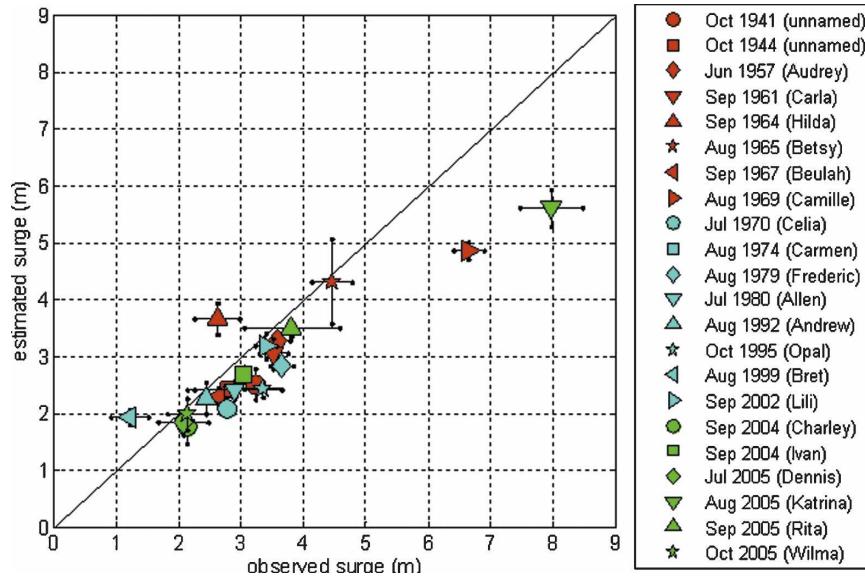


FIG. 7. Estimated vs observed peak surge. Horizontal error bars represent the range of observed peak surge in the vicinity of expected maximum alongshore surge to the east of the hurricane eye at landfall. Vertical error bars represent the range of estimated peak surge as it relates to the range of bottom slopes in the region of landfall.

the surge estimate is lower than that observed. There are a number of reasons why this occurs. First, the numerical simulations are idealized and do not represent the complex topography of the New Orleans area where the regional-scale Mississippi River Delta feature would result in additional surge levels to the east of this feature. Additionally, surge response to localized geographic features, particularly shallow back-bay areas, can also significantly influence localized wind setup. Indeed, the largest observed surge during Hurricane Katrina occurred inside Bay St. Louis, Mississippi, a localized feature not considered in this study. Second, wave setup is not included. For Hurricanes Camille and Katrina, wave setup was on the order of 1.5 m (U.S. Army Corps of Engineers 2006a). Third, both Hurricanes Camille and Katrina approached the coast from the southeast. While Hurricane Katrina turned due north during final approach, Hurricane Camille maintained an approach angle of 20°, measured counterclockwise from a due north approach. The surge estimate is based solely on storms following a due north track, and, as Fig. 4 demonstrates, a reduction in peak surge by about 8% is expected for more northwesterly tracks. Fourth, the storm forward speed at landfall for both Hurricanes Camille and Katrina was about 6.7 m s⁻¹ and is 30% higher than the uniform forward speed used in determining the surge estimates. As Fig. 5 illustrates, an increase in surge on the order of 5% can be expected for these two storms making landfall in the New Orleans area. Finally, the idealized wind and pres-

sure fields for these storms may not capture all of the details of the surge generation process at the coast in these two storms. Nonetheless, the numerical simulations revealed that the physical phenomena governing surge generation does explain why the surge from Hurricane Katrina was larger than that from Hurricane Camille, and this is validated by the observations. Further, these two storms emphasize the importance of storm size on surge generation. Finally, our results indicate that a landfalling storm the size of Hurricane Camille, which is also characterized by the tropical cyclone maximum possible intensity (MPI) for the Gulf of Mexico, on the order of 880 mb (Tonkin et al. 2000), cannot produce a surge as large as that produced by a storm the size of Hurricane Katrina.

6. Conclusions

Research from the late 1950s through the 1970s concluded that, based on observations from historical hurricanes, the influence of storm size on surge was relatively small. At that time, the historical dataset included only hurricanes from small to moderate size and intensity. The data used for this conclusion were taken solely from high-water marks, which contain considerable scatter, making it difficult to distinguish possible storm size-related effects. Given the lack of observational motivation, no systematic study of the potential impact of storm size on coastal storm surges via either theoretical or numerical methods had been conducted prior

to Hurricane Katrina. The lack of clear observational evidence and theoretical studies on the impact of storm size led to the implicit neglect of the potentially catastrophic role that this could play in coastal surges.

Our analysis of observed recent and historical storm data along with idealized numerical simulation data demonstrate that storm size plays a key role in hurricane surge generation in coastal areas, particularly for the case of intense storms on very shallow slopes. Thus, while the Saffir–Simpson scale has historically provided an adequate categorization of hurricane wind damages, it does not provide a reliable estimate of expected hurricane flooding damages.

As a good example of the importance of this effect, our results indicate that a hurricane of Camille’s size, even if that storm attained the maximum possible intensity (MPI) for the Gulf of Mexico (around 880 mb), could not produce a storm surge along the Mississippi coast of the same magnitude as that of Hurricane Katrina. Thus, although Hurricane Katrina was only a category 3 storm, it represents a much more serious coastal flooding threat than small category 5 storms.

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APPENDIX

Best-Fit Lines for Surge Relationship

While not recommended for use as a surge model, a best-fit relationship to our simulation results provides useful insight regarding the coupled impact of hurricane size along with hurricane intensity and shelf slope. A polynomial curve fit was developed using the numerical simulation data by considering, in order, 1) ζ versus R_{\max} , where Δp and S_o are constant, and 2) the variation of ζ versus R_{\max} as Δp varies. The resulting relationship is

$$\sqrt{\hat{\zeta}} = \left[\sqrt{\widehat{R_{\max}}} 1 \right] \left\{ C(S_o) \begin{bmatrix} \widehat{\Delta p^2} \\ \widehat{\Delta p} \\ 1 \end{bmatrix} \right\}, \quad (\text{A1})$$

where $\widehat{\quad}$ indicates a dimensionless quality and

$$\hat{\zeta} = \frac{\zeta g}{V_{\max}^2}, \quad (\text{A2})$$

$$\widehat{\Delta p} = \frac{\Delta p}{p_{\text{atm}}}, \quad (\text{A3})$$

$$\widehat{R_{\max}} = \frac{R_{\max} g}{V_{\max}^2}, \quad (\text{A4})$$

$$C(S_o) = 2 \times 3 \text{ curve-fitting coefficient matrix:} \quad (\text{A5})$$

$$\begin{aligned} S_o = 1:250 & \begin{pmatrix} -2.159 \times 10^{-2} & 1.593 \times 10^{-2} & 6.674 \times 10^{-4} \\ 4.211 \times 10^{-1} & -1.813 \times 10^{-1} & 7.242 \times 10^{-2} \end{pmatrix}, \\ S_o = 1:500 & \begin{pmatrix} -3.585 \times 10^{-2} & 1.753 \times 10^{-2} & 6.767 \times 10^{-4} \\ 8.539 \times 10^{-1} & -2.877 \times 10^{-1} & 8.833 \times 10^{-2} \end{pmatrix}, \\ S_o = 1:750 & \begin{pmatrix} -3.460 \times 10^{-2} & 1.751 \times 10^{-2} & 6.581 \times 10^{-4} \\ 1.176 \times 10^0 & -3.880 \times 10^{-1} & 1.032 \times 10^{-1} \end{pmatrix}, \\ S_o = 1:1000 & \begin{pmatrix} -1.329 \times 10^{-2} & 1.403 \times 10^{-2} & 8.424 \times 10^{-4} \\ 1.124 \times 10^0 & -4.078 \times 10^{-1} & 1.111 \times 10^{-1} \end{pmatrix}, \\ S_o = 1:2500 & \begin{pmatrix} -9.340 \times 10^{-2} & 3.072 \times 10^{-2} & 3.080 \times 10^{-4} \\ 2.888 \times 10^0 & -8.063 \times 10^{-1} & 1.459 \times 10^{-1} \end{pmatrix}, \\ S_o = 1:5000 & \begin{pmatrix} -1.078 \times 10^{-1} & 3.996 \times 10^{-2} & 4.444 \times 10^{-4} \\ 3.974 \times 10^0 & -1.093 \times 10^0 & 1.653 \times 10^{-1} \end{pmatrix}, \text{ and} \\ S_o = 1:10\,000 & \begin{pmatrix} -1.369 \times 10^{-1} & 4.937 \times 10^{-2} & 7.558 \times 10^{-4} \\ 4.845 \times 10^0 & -1.301 \times 10^0 & 1.731 \times 10^{-1} \end{pmatrix}. \end{aligned}$$

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