The interacting effects of storm surge intensification and sea-level rise on coastal resiliency: a high-resolution turbulence resolving case study

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Abstract
Climate change and global warming will increase the risk of coastal floods and storm surges, which can highly jeopardize communities and infrastructures along shorelines. There are two main drivers for this increase: surge amplification, which is caused by the projected hurricane intensification, and global sea-level rise (SLR). Although both factors can simultaneously affect storm surges, current knowledge on their interacting effects on the resiliency of coastal infrastructure is limited. To address this knowledge gap, we investigate the impacts of multiple storm surge scenarios on vehicles and buildings by varying wave heights, periods, and sea levels under current mitigation strategies. These surges are highly turbulent due to their high speed and wave-wave/bathymetry interactions. Large-scale numerical simulations with low-resolution (∼1–5 km) and depth-integrated models that do not resolve turbulence cannot assess the thorough impacts of these storm surges on infrastructures accurately. Hence, we employ a high-resolution numerical approach that is capable of resolving turbulent eddies down to ∼3 cm and capturing fluid-structure interactions. The distribution of hydrodynamic loads is found to vary nonlinearly in all directions with surge amplification and can significantly exceed calculations from classical theories that neglect turbulence. Two approaches from previous experiments are employed in a novel way to evaluate the resiliency of vehicles and infrastructure during storm surges. Our results indicate that vehicle mobility on the considered road will be imperiled by moderate surges (4 m wave height), and the elevated building will fail by surge intensification (8 m waves). We found that some storm-surge wave heights that are relatively safe now (e.g., 2 m waves for vehicles and 6 m for the building) will become hazardous in the future with an SLR. Therefore, road and building safety regulations should account for the interacting effects of hurricane intensification and SLR when devising mitigation strategies.

1. Introduction
A storm surge is an increase in the sea surface beyond normal tides that occurs when water is pushed by strong winds swirling around low-pressure weather systems such as hurricanes [1]. The advancing surge, affected by the wave characteristics and the bathymetry relative to the storm path, can increase the sea-level (SL) by 10 m or more, taking out boats and buildings, and overflowing rivers and lakes.

For shallow coastal areas, storm surge generates hazardous waves and floods, particularly if the surge coincides with the tidal phase [2]. For instance, Hurricane Katrina in 2005 induced one of the strongest surges by creating 8 m waves near Louisiana coastlines [3] and resulted in billions of dollars in damages [4]. Other catastrophes that struck shallow coastal regions include Maemi (2003) in the Korean Masan Bay costing more than $4.3 billion in damages [5], and Sandy (2012) in New York [6] costing more than $21 billion. Hurricanes have been the costliest natural disaster in US history, surpassing droughts and earthquakes [7]. Hence, it is
imperative to assess current storm surge mitigation strategies and devise efficient plans to protect low-lying coastal areas from future storms.

Recent research has shown that extreme storm surges and floods are becoming more frequent [8, 9]. Two factors that can simultaneously increase the risk of storm surges are hurricane intensification and sea-level rise (SLR). Recent climate studies predict an amplification of major hurricanes in response to the warming sea surface temperatures [10–13]; this means stronger hurricane winds [14], which would lead to more extreme storm surge waves. The global SLR has accelerated over the last century [15] and is projected to further rise in the future, threatening infrastructures and ecosystems [16–20]. Therefore, storm surges are projected to increase in frequency and magnitude [21, 22].

Numerical simulations of storm surges have provided a robust tool to evaluate risks associated with these extreme events. For instance, the effects of SLR on hurricane storm surges and their inundation level risks have been characterized [23] using a tightly coupled Simulating Waves Nearshore with ADVanced CIRCulation (SWAN + ADCIRC) model [24]. The socio-economic impacts of storm surges have also been studied using ADCIRC [25] and the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model [26]. A one-dimensional hydrodynamic model was used to assess the risks of sea-surface temperature rise and SLR on storm surge floods [27]. Rego and Li (2010) employed a Finite-Volume Coastal Ocean Model (FVCOM) to study the impact of Hurricane Ike’s surge. They utilized a mesh resolution of ~500 m with the finest mesh of 180 m and showed that resolutions of 250 m or higher cause unrealistic surges. Bertin et al. [1] used a storm surge simulation that couples a two-dimensional (2D) circulation model [28, i.e., Zhang & Bapista 29] with a wave model [30] to analyze the contribution of short-waves to surges.

Although these models have been very useful in describing the large-scale behavior of storm surge (e.g., for the entire Gulf of Mexico), they inadequately describe it on the small-scale. This is mainly due to two reasons: (1) many physical aspects of the storm surge phenomena, such as turbulent eddy motions, are not fully realized by such numerical models, and (2) the implemented grid resolution is so coarse (a minimum of ~180 m [31–32]) that the wave-wave [33] and wave-bathymetry interactions [32] are not resolved accurately. The low resolution is partly because of the computational cost of turbulence-resolving numerical schemes that remains out of reach, given available computational power. For example, many of the Numerical Weather Prediction and General Circulation Models (e.g., ADCIRC), do not resolve three-dimensional (3D) turbulence using the full Navier–Stokes (NS) equations [34]; they instead typically employ a 2D depth-integrated shallow water model. Shallow water models consider one grid cell in the vertical direction by integrating all variables that vary with depth. This simplification decreases the computational expenses at regional length scales (~100–1000 km), albeit with a lower accuracy compared to the full 3D NS solutions. It is thus indispensable to address this tradeoff between computational feasibility and accuracy in such models by improving their parameterizations with the help of more accurate high-resolution simulations.

Despite many studies on the storm surge phenomenon, the interacting effects of storm surge amplification and SLR on the resilience and small-scale stability of coastal infrastructure are not well understood, nor well predicted. The objective of this paper is to bridge this knowledge gap by using a high-resolution (~0.03–0.3 m) large-eddy simulation (LES) technique that sheds light on the turbulence structure of the storm surges. LES represents a high-fidelity framework that allows us to understand and model turbulence dynamics in high-Reynolds number fluids [35, 36] by explicitly resolving large energy-containing eddies. In particular, we will answer the following questions:

1. What are the interacting effects of storm surge intensification and SLR on the dynamics of the surge, and which flow parameters should be considered when assessing mitigation strategies?
2. How can high-resolution LESs, which resolve turbulence, offer more insights into the storm surge phenomenon?
3. How effective are the current mitigation strategies under the interacting effects of storm surge intensification and SLR over the coming decades?
4. What are the implications of high-resolution LESs for regional storm surge models, and how can they help to improve large-scale storm surge predictions?

We will focus on the resiliency of vehicles and buildings in coastal areas under multiple surges and SLR scenarios. Studies of vehicle stability during a storm surge have primarily focused on flooding caused by street drainage failure under intense rainfall [37–40]. Previous studies of building resiliency mainly analyzed a city’s building-code efficiency and its capability in dealing with storm surges [41], or assessed a building’s structure to withstand various flood forces [42, 43].
The Galveston Beach area on the Gulf Coast of Texas was chosen as our focal point due to the high occurrence of hurricanes in this area (e.g., Harvey in 2017 [44], Ike in 2008 [45, 46], and Rita in 2005 [47]). In 1900, Galveston Island experienced the deadliest natural disaster in the US, "The Great Galveston Hurricane," which killed over 6000 residents and destroyed over 2500 homes [48, 49].

The paper has the following structure. Section 2 describes the employed methodology, the characterization of the waves around the study area, and an overview of the full parameter space of the problem. Section 3 details the results of the simulations by presenting the analyses of both vehicle and building mitigation strategies. The implications of the results and the advantages of high-resolution turbulence-resolving simulations for regional storm surge models (e.g., SLOSH) are also discussed in this section. Section 4 provides a summary of the main findings of the paper.

2. Methods

2.1. Numerical methodology

The computational fluid dynamics code OpenFOAM is used to conduct high-resolution simulations of storm surge flows. The code solves the filtered incompressible continuity and Navier–Stokes equations as

\[ \nabla \cdot \tilde{u} = 0, \]

\[ \frac{\partial \tilde{u}}{\partial t} + \tilde{u} \cdot \nabla \tilde{u} = -\frac{1}{\rho} \nabla \tilde{p} + \nabla \cdot (\nu (\nabla \tilde{u} + (\nabla \tilde{u})^T)) + \frac{\nabla \cdot \tau}{\rho} + \tilde{g} \]

where tildes denote filtering at grid-scale, \( \tilde{u} \) is the resolved velocity vector, \( t \) is time, \( \rho \) the density, \( \nu \) the resolved pressure, \( \nu \) the mixed kinematic viscosity, \( g \) the acceleration of gravity, and \( \tau \) the subgrid-scale (SGS) stress tensor, which is parameterized using the Smagorinsky model ([50]; supplementary section S2.1 available online at stacks.iop.org/ERC/2/115002/mmmedia).

The multi-phase flow (gas-liquid) solver interFoam is employed in this study (supplementary section S2.2). It has been extensively evaluated and validated against experiments [35, 51]. The properties of the fluid at each cell are calculated by weighting them through a phase indicator function, \( \alpha \), as demonstrated below for the density

\[ \rho(\bar{x}, t) = \alpha(\bar{x}, t) \rho_{\text{water}} + (1 - \alpha(\bar{x}, t)) \rho_{\text{air}}, \]

where \( \alpha = 1 \) denotes liquid (here seawater), \( \alpha = 0 \) means gas (here air), and \( 0 < \alpha < 1 \) represents their interface. To track the interface changes, the solver employs a modified volume of fluid (VOF) approach ([52]; Please see section S2.2 in the supplementary materials).

The wave2Foam package is used to generate the storm surge waves; its accuracy in wave generation is demonstrated in previous studies [52–55, i.e., Huang et al 28]. In addition, we have validated this code against two laboratory experiments [56, 57]. The first validation case assesses the solver’s accuracy in predicting the hydrodynamic forces on a structure, and the second evaluates its capability in generating correct water waves. The results for both cases agree well with the experiments. More details about the wave generation methodology and code validations can be found in the supplementary sections S2.3 and S2.4.

2.2. Case selections and the numerical domain

The SL on the Galveston coast increases to a mean of 0.38 m during high tides (nighttime) and drops to 0.076 m during low tides (daytime; [44]). Since the study focuses on risk assessment of extreme events, the critical SL, which is the mean high water (MHW) level (figures 1(a)–(d), is chosen as the reference scenario.

Two locations close to the MHW line on the Galveston coast are chosen to simulate the coastal resiliency of vehicles and buildings. The first location (figures 1(a), (b)) is used for the vehicle resiliency simulations and is located on Seawall Boulevard. The road is 15 m wide and ~50 ft away from the MHW line at this location. This road has been elevated by 15 ft from the SL to avoid potential storm hazards (figure 1(b)). A schematic diagram of the simulation domain and grid cells is depicted in figure 1(e). A grid refinement is conducted to increase the resolution on the road (0.03 m vertical cell size; see supplementary section S3 for more details).

The second location on the Galveston coastline is for a building located 9 ft above and 180 ft away from the MHW line (figures 1(c), (d)). Most coastal buildings in the Galveston area follow the National Flood Insurance Program (NFIP) and the Federal Emergency Management Agency (FEMA) regulations concerning the reduction of flood damages [58]. The building chosen for the current case study falls under Zone V, a special flood hazard area. FEMA regulations recommend buildings in this zone to elevate the lowest floor level above the Base Flood Elevation (BFE) level [58], and to calculate design loads under the assumption that the flood level will exceed BFE.
The simulated building is 14.1 m long, 11.2 m wide, and 6 m high. The building is elevated 3 m above the ground level by ten columns with a cross-sectional area of about 0.32 m². To capture all turbulent motions around the building, a 3D numerical domain is utilized (figure 1). The grid resolution of these simulations near the building is set to 0.33 m³ to allow resolving columns and detailed fluid-structure interactions (see supplementary section S4).

In addition to the two sites described above, two more locations outside the Galveston Beach area are chosen to examine the impact of bathymetry and topology on the generality of the main findings. The third considered site is located on North Fort Lauderdale Beach Boulevard in Fort Lauderdale, Florida (figure 4(a)). The road is 20 m wide and ~30 m away from the MHW and is not elevated, unlike the chosen road in the Galveston area. The last studied site is located on Beach Boulevard in Biloxi, Mississippi (figure 4(b)). The road is 20 m wide and ~20 m away from the MHW. This road differs from the previous roads by having a slope as it is located on a hillside. A schematic diagram of the simulation domains and grid cells for these locations are depicted in figures 4(c), (d).

### 2.3. Suite of large-eddy simulations

To study the interacting effects of storm surge intensification and SLR, three scenarios are chosen, each referencing the SL at a different time. Scenario 1 is for the current MHW, which is 0.38 m above the normal SL [59]. Scenario 2 represents the MHW in the year 2050, which is predicted to increase by about 0.83 m above the current average SL [60, 61]. Scenario 3 will be the MHW in the year 2100, which is predicted to rise by about 1.38 m above the current SL [62].

To comprehensively assess the parameter space of storm surges, multiple wave heights and periods are simulated. The chosen wave characteristics are derived from real gauge measurements near Galveston Beach (figure 2(a) and table S1). The measurements for six hurricanes that made landfall in or close to Texas are used (see supplementary table S2 for more details). Figure 2(b) depicts the recorded storm surge wave heights and...
The suite of large-eddy simulations conducted for assessing vehicle stability and mobility over Galveston coastal road, where X can be 1, 2, or 3. Sc1 represents current the MHW level (+0.38 m), while Sc2 and Sc3 denote future MHW levels (+0.83 m) and (+1.38 m) respectively. In total, $5 \times 3 \times 3 = 45$ simulations are conducted to evaluate the resiliency of vehicles on the road under various storm surge events. The coordinates of the chosen location are (N 29° 15' 18", W 94° 30' 47"). The vertical grid resolution of these simulations on the road surface is 0.03 m.

| Wave height | 2 m  | 3 m  | 4 m  | 6 m  | 8 m  |
|-------------|------|------|------|------|------|
| Period = 8 s ScX_H2_T8 ScX_H3_T8 ScX_H4_T8 ScX_H6_T8 ScX_H8_T8 |
| Period = 10 s ScX_H2_T10 ScX_H3_T10 ScX_H4_T10 ScX_H6_T10 ScX_H8_T10 |
| Period = 12 s ScX_H2_T12 ScX_H3_T12 ScX_H4_T12 ScX_H6_T12 ScX_H8_T12 |

The suite of large-eddy simulations conducted for examining the impact of the bathymetry and topology on the generality of vehicle stability findings, where X can be 1 or 3. Sc3 denotes future MHW levels (+1.38 m). In total, $4 \times 2 \times 2 = 16$ simulations are conducted to evaluate the resiliency of vehicles on two roads under various storm surge events. The coordinates of the chosen locations in Florida (FL) and Mississippi (MS) are respectively (N 26° 07' 52.6", W 80° 06' 11.7") and (N 30° 23' 26.1", W 88° 58' 36.1°). The vertical grid resolution of these runs on the road surface is 0.03 m.

| Wave height | 2 m  | 3 m  | 4 m  | 6 m  |
|-------------|------|------|------|------|
| Florida     ScX_H2_T10_FL ScX_H3_T10_FL ScX_H4_T10_FL ScX_H6_T10_FL |
| Mississippi ScX_H2_T10_MS ScX_H3_T10_MS ScX_H4_T10_MS ScX_H6_T10_MS |

The chosen simulated wave heights are 2, 3, 4, 6, and 8 m waves, which capture the dynamics of both small and large storm surges. Although an 8 m wave has not been measured by the gauges, the study considers this extreme wave height to account for potential hurricane intensification in the future. For the wave periods, 8, 10, and 12-second periods are chosen, consistent with the storm surge measurements. Longer periods (> 12 s) will not be shown here as they are less prevalent, and they do not lead to severe inundations compared to the chosen periods.

Table 1 summarizes the 45 simulated cases for the coastal vehicle resiliency, organized by wave height and period, while reflecting the three SL scenarios previously described. The cases are labeled according to their scenario (Sc), wave height (H), and wave period (T). Table 2 summarizes the 16 simulated cases for investigating the impact of bathymetry and topology on vehicle resiliency over the considered coastal roads of Florida (FL) and Mississippi (MS). The cases are organized by wave height, while reflecting the two SL scenarios—the current SL and the SL of the year 2100. Table 3 summarizes the nine simulated cases for the coastal building resiliency simulations. Only one period will be shown here (10 s) for the last two sets of simulations since other periods

Figure 2. (a) Map showing the locations of the five stations near the Galveston Beach area that are used to estimate storm surge characteristics in this region. Twenty years of measured data (2000–2020) are obtained from the Wave Information Study (WIS) group or the National Data Buoy Center (NDBC). (b) Average wave period versus the average wave height during six hurricanes that passed through Galveston Beach. The measured data from the stations are shown as dots, while their average is represented by a dashed-dotted line, and the shaded area depicts two standard deviations from the average.
provided similar conclusions. Smaller waves (<4 m) did not have a significant impact on the resiliency of the chosen building and will not be presented here.

### 3. Results and discussion

#### 3.1. The resiliency of vehicles on coastal roads under extreme storm surge events

The stability of partially submerged stationary cars in flooded streets has been previously investigated \[63–65\]. Using experimental data \[64, 65\], a critical dimensionless curve was introduced as the safety criterion for flooded parked vehicles \[63\]:

\[
\frac{H_{ci}}{H_v} = -0.05 Fr + 0.34, \tag{4}
\]

where \(H_{ci}\) is the critical inundation depth, and \(H_v\) is the vehicle height. \(Fr\) denotes the flow Froude number defined as,

\[
Fr = \frac{U}{\sqrt{gH_v}}, \tag{5}
\]

where \(H_v\) represents inundation depth, and \(U\) is inundation speed. If the measured ratio \((H_v/H_{ci})\) is greater than the critical ratio \((H_v/H_{ci})\), then the vehicle is considered unsafe as it will have incipient motion due to water movement; otherwise, it is safe. This criterion will be employed here using our LES results in a novel way to investigate the vulnerability of vehicles to extreme storm surges.

To probe the stability of vehicles under different storm surge scenarios, 45 high-resolution simulations are conducted in the Galveston Beach area (table 1). Figures 3(a), (b) show two examples of our simulation results that depict the wave breaking near a steep slope. The figure reflects a collapsing wave (figure 3(a)), and a plunging wave (figure 3(b)) that are two of the four breaking mechanisms in the wave breaking theory \[66\]. Wave breaking is a critical physical mechanism in surges that needs to be captured in any numerical model to accurately represent storm surge impacts. Such mechanisms have been shown to impact the upper ocean structure and mixing \[67\]. The effects of wave breaking are typically parameterized either as a surface energy flux in the turbulent kinetic energy equation or a stress flux in the momentum equation. Accounting for such processes was shown to remarkably improve the performance of large-scale ocean models \[68\]. Therefore, considering these mechanisms in surge models is vital; however, the addition of wave-bathymetry interactions in shallow coastal areas can make such parameterizations challenging. High-resolution LESs can be employed to parameterize such processes in regional surge models (see, e.g., section 3.3).

Twenty gauges are uniformly distributed over the first 10 m portion of the road (figure 1(a)), each measuring the \(H_v\) and the \(Fr\) at all intervals. Figures 3(c), (d) present the spatially averaged \(H_v\) and \(Fr\) recorded by the gauges for three cases. The ratio of the inundation level over the vehicle height \((H_v/H_{ci})\) versus the \(Fr\) is shown in figures 3(e)–(g) for all gauges in three cases (see supplementary figures S9, S10, and S11 for others cases). The critical ratio curve in equation (4) is depicted as a dotted black line in scatterplots. The color of the scatterplots is an indicator of the degree of safety, with green being safe and red being hazardous. Note that for the vehicle height, we consider an average sedan size with equal to 1.45 m to calculate the points in the scatterplots.

A storm surge case is considered to be safe for cars when all the points in this graph fall below the critical stability curve. Figure 3(e) presents the current SL scenario (Sc1) with a low wave height (H2) case; the figure shows all points as green and below the critical curve indicating that the storm surge case Sc1_H2_T10 is completely safe for vehicles on the considered road. Figures 3(f), (g) present cases with a medium wave height (H4), but with different SL scenarios (current SL and elevated SL due to climate change). The figure shows that
the case with an elevated SL has more points in the unsafe region (fewer green dots in 3 g compared to 3 f). This demonstrates that the SLR modulates the safety levels and resiliency of vehicles on coastal roads.

The scatterplots data of all cases are employed to derive an exhaustive understanding of the interacting effects of storm surge intensification and SLR. Figures 3(h) and S12 present a summary of the average danger level of all simulated cases for the current mitigation strategy (elevated road). The data for each case is calculated by taking the ratio of the unsafe points in the scatterplots over the total points across all gauges. Figure 3(h) indicates that the current mitigation strategy (road elevation by 15 ft) is effective for Sc1_H2 cases. However, it fails to protect cars in higher wave heights as there will always be some risks for such waves (figure 3(h)). Hence, in the current situation without any change in the SL, the mitigation strategy can only be fully effective for a wave height of \( \leq 2 \) m. An increase of the wave height by 1 m can increase the risk of vehicle inundation on this road by \( \sim 4\% - 54\% \) depending on the SL (supplementary figure S13).

The wave periods have a nonlinear effect on the safety level of a storm surge. This nonlinear response is associated with the nonlinear dynamics that dominate these surges due to the bathymetry, SL, wave height, and wave-wave & wave-turbulence interactions. The results in figures 3(h) and S12 indicate that the wave period...
modulates the safety levels in smaller wave heights (2 and 3 m) more significantly while larger wave heights (6 and 8 m) will always be hazardous irrespective of their wave period.

To accurately assess the resiliency of the road, SLR and its interacting effects with the surge intensification should be considered. Figure 3(h) shows that an SLR will increase the danger level for current safe cases. For instance, while H2 cases were almost safe in the current SL, they will no longer be safe with an SLR in the future. This is evident when you consider case H2_T10 with a 2 m wave height; it is safe for low SLs with a danger likelihood of \(\sim 0.04\%\) but increases to \(\sim 37\%\) with the highest SL (predicted SL for the year 2100). In general, SLR consistently increases the danger levels in all cases.

We modified the current elevated road design in a separate simulation by adding barrier walls and a drainage system and noticed a significant reduction in the danger level of extreme storm surge cases (see supplementary figures S14 and S15). Hence, we suggest building barrier walls with proper drainage systems or further elevating the road to reduce the interacting risks of storm surge intensification and SLR on the considered road. The design of such systems can be optimized using similar high-resolution simulations to increase the safety level of coastal roads.

To corroborate the generality of our main findings regarding the interacting effects of storm surge intensification and SLR, we conducted additional simulations for two locations outside the Galveston area. The topology and bathymetry of the two locations (in Florida and Mississippi) are different from the considered coastal road in Galveston, as shown in figures 4(a)–(d). The coastal road in Florida is not elevated above the beach as the road in Galveston, while the Mississippi coastal road is on a slope. Eight simulations for each location are conducted by varying SL and wave heights (table 2).

The results of the simulations for these two locations are consistent with the main findings for the considered road on Galveston Beach. Figures 4(e), (f) present the summary of the average danger level of all simulated cases for the two locations. While the maximum safe wave height for any coastal road should naturally depend on the bathymetry and topology, the main trends in all cases are expected to remain similar. The 3 m wave height, for...
example, is relatively harmless in Florida (∼0.97% danger level, figure 4(e)) and Galveston (∼3.98% danger level, figure S12), while the danger level is orders of magnitude higher in Mississippi (∼51%, figure 4(f)) making a 3 m wave height unsafe for this region. This could be due to the proximity of the considered road to the shoreline compared to the road in Florida and its lower elevation compared to the road in the Galveston Beach area.

Nevertheless, increasing the wave heights consistently elevates the risk of storm surges and makes them hazardous irrespective of the topological nature of the considered sites (figures 3(h), 4(e), (f)). As for the SLR, the figures indicate that an increase in the SL is accompanied by an increase in danger levels for all wave heights regardless of the bathymetry or topology. In general, the results show consistency across different topologies in terms of the SLR impact on storm surges and danger levels of large wave heights.

3.2. The resiliency of coastal buildings under extreme storm surges

Nine simulations are conducted to examine the interacting effects of storm surge height and SLR on the considered building in the Galveston Beach area (table 3, figures 3(d), (f)). The results showed the highly turbulent and chaotic nature of large storm surges. The Reynolds number of such flows ($Re = UHi/\nu_{seawater}$) in the simulations can reach up to $\sim 4 \times 10^6$. Figure 5 shows the progression of a wave from case Sc1_H8_T10 approaching the building: 5b,c color the seawater according to the streamwise velocity with red being fast and blue being slow. It also depicts the Q-criterion ($\frac{1}{2} \text{tr} (\nabla \mathbf{u}^2) = \frac{1}{2} \text{tr} (\nabla \mathbf{u}^2)$; [69]) of turbulent eddies as green structures. The propagation of the high momentum wave toward the building creates streamwise elongated shear-induced streaks in its wake (structure 1 in figure 5(b)). The wave itself forms a spanwise turbulent structure due to its vorticity that is caused by breaking processes (structure 2 in figure 5(b)). Once the wave collides with the building, it loses its energy and creates disorganized eddies (structure 3 in figures 5(b), (c)). Then, this wave goes back toward the shoreline. On its way back, the downgoing low-momentum wave (blue color in figure 5(c)) collides with a fresh high energy upgoing wave (red color in figure 5(c)), producing a highly turbulent and nonlinear flow (figure 3(a) and structure 4 of figure 5(c)). It also creates highly chaotic disorganized eddies that can reduce the energy of the high momentum wave (structure 5 of figure 5(c)).

To assess the impact of the storm surges on the building more accurately, the columns of the building are resolved in our simulations. Figures 6(a), (b) show the wave-column interaction upon the first impact and as the wave passes through the building. Figures 6(c), (d) depict the vorticity contour ($\nabla \times \mathbf{u}$) through the building.
before and after a wave passes through. The building structure and columns increase the turbulent mixing in the storm surge flow (figures 6(c), (d)).

These three-dimensional high-resolution simulations allow us to accurately estimate the stormwater loads on the building. Figures 6(e), (f) display the stresses caused by the hydrodynamic forces of the incoming waves on the building. Although in a typical laminar flow the maximum hydrostatic pressure occurs at the surface, this is not necessarily the case in our simulations due to the highly turbulent nature of the studied surges. As figure 6(f) indicates, at some instances, there can be stress peaks above the surface (see the stress at ∼2 m above the ground that is higher than the stress near the surface). These peaks are caused by turbulent eddies and high momentum bulges that instantaneously smash into the building. Therefore, classical theories that neglect such turbulent motions cannot accurately predict the maximum stormwater load and moment on buildings. The nonlinear distribution of stormwater forces (in all directions) and their maximums (higher than the typical hydrostatic force calculations) caused by turbulence should be considered for designing resilient structures.

Increasing the storm surge height also has a nonlinear effect on the total stormwater load on the building. Figures 7(a), (b) present the stress and inundation levels experienced by the front side of the building for the current SL. The figure shows that a linear increase in the wave height causes a nonlinear increase in the stress and inundation levels.

To comprehensively assess the interacting effects of storm surge height and SLR, the total stress on the building and inundation level for all nine cases are investigated. Figures 7(c), (d) present a summary of the average and 95 percentile danger levels for each case compared to the critical height. The considered building has been elevated to about 3 m above the ground level, suggesting that 3 m is the critical inundation height in this case (i.e., $H_{ci} = 3$ m). The figure shows that the considered cases with wave heights below the 4 m threshold are safe regardless of SLs. Hence, the current mitigation strategy (elevated building height) will be effective for up to ∼4 m storm surge height in this area.

SLR can make current safe storm surge heights hazardous in the future. For instance, for cases with a 6 m wave height, they are safe for the current SL, but unsafe with SLR. This is evident when considering...
Sc1_H6_T10, which is relatively safe for the current SL with an inundation level \( \leq 2.4 \) m, while the higher SL scenarios (Sc2_H6_T10 and Sc3_H6_T10) surpass the critical inundation height. Storm surge intensification can significantly endanger the current coastal infrastructure. For example, the average inundation level of 8 m wave height exceeds the critical level \( H_{ci} = 3 \) m for all scenarios, while its 95 percentiles are near the top of the building. Therefore, storm surge intensification and SLR can both lead to the failure of the building and current mitigation strategies.

### 3.3. Implications of high-resolution turbulence-resolving simulations for improving coastal risk assessment in regional storm surge models

The impacts of future storm surge scenarios on the resiliency of coastal infrastructure were exhibited in sections 3.1 and 3.2 by conducting simulations with a domain size of the order of 100 m. Here, we briefly examine the implications of these high-resolution small-scale LESs for improving the state-of-the-art in storm surge modeling at a large regional scale (domain size of \( \sim 100–1000 \) km). In particular, we focus on SLOSH, which is NOAA’s operational storm surge forecast model. Regional storm surge models provide a useful tool for real-time prediction of inundation levels under hurricane storm surges. Such large-scale models play a significant role in decision making for evacuation orders and for devising mitigation strategies in coastal regions.

The governing equations of SLOSH are 2D and are integrated from the sea floor to the surface with bottom slip coefficients to account for the bathymetry [70]. This implies that SLOSH does not resolve 3D turbulence, nor does it consider wave-turbulence interactions. Although SLOSH can provide quick analyses of vulnerability to storm surges, studies by Blain et al [71] and Morey et al [72] showed deficiencies in SLOSH when employing small domains. Kerr et al [73] also noted that SLOSH’s local meshes failed to capture regional processes in Hurricane Ike. These shortcomings were associated with its low resolution and missing internal physics and frictional parameterizations [73].

The current section provides some guidance on how high-resolution turbulence-resolving LESs can be used to improve the accuracy of SLOSH predictions for coastal risk assessment studies. To achieve this task and to be consistent with previous sections, we chose Hurricane Ike as our reference case, and the Galveston area as our reference basin (see the domain and SLOSH grids in figure 8(a)).

We focus on comparing the high-resolution LES results with SLOSH’s outputs for one grid cell in the Galveston beach area (main grid in 8b). Please see supplementary material S5 for details about the implemented methodology and the justification for running the LES cases given the stark scale contrast of these two models.

Eight wave heights were extracted every \( \sim 3.4 \) h from SLOSH’s outputs (neighboring cells in 8b) and were used as input wave heights in our LESs to generate storm surges over land (main grid cell in 8b). We then...
compare the surge height of the LES runs to the SLOSH’s storm surge outputs in the main grid (blue line in 8d). The surge height for our LESs was calculated by averaging the inundation levels above the land. Two LES bathymetries (8c) were selected to partially account for the surface inhomogeneities (see supplementary material S5 for justification). After conducting eight wave height LESs for each two bathymetries, the average of the surge levels of the two simulations is displayed as black dots in figure 8(d). The shaded area represents the 10th–90th percentile range of the LES results.

When comparing the surge level depicted by the ‘main’ SLOSH grid to our generated levels using multiple LESs ‘LES Avg’, several differences appear (figure 8(d)). The first difference is that SLOSH results show a delay between the surge on the land and its sea surge counterparts. SLOSH water grid cells S, E, and SE reach a peak surge on 09/13 at 4:00, while their neighbor land cell ‘SLOSH main’ reached its peak ∼4 h later. The peak surge for LES, on the other hand, occurred at the same time as the water grid cells, consistent with the neighboring SLOSH grids. Furthermore, after 09/13 at 7:00 SLOSH’s outputs for the main grid cell are greater than the average of LESs over land while they are within the 90th percentile of the LES results.

These discrepancies could be associated with the vast differences in the resolution, governing equations, and parameterizations in the two considered models. In particular, neglecting turbulence mechanisms and the wave-wave/bathymetry interactions can lead to inaccurate surge predictions in SLOSH. To improve this deficiency, we propose coupling the low-resolution regional surge models with high-resolution LESs that are capable of capturing the small-scale turbulent physics, particularly near coastal areas where the surge flows from sea to land. A nested domain approach could be implemented where SLOSH data are given to LES (with a
potential feedback loop) similar to Weather Research and Forecasting Model [74]. Another suggestion is to improve the sub-grid scale parameterizations in such large-scale models by accounting for wave-wave, wave-bathymetry, and wave-turbulence interactions. Our LESs can help to characterize the effects of such small-scale processes on surge dynamics in the whole parameter space of the problem. Advancing these surge models will provide more accurate coastal risk assessments at a regional scale and, thus, will rectify the current mitigation strategies.

4. Conclusion

The current paper investigates the interacting effects of storm surge intensification and SLR on the coastal resiliency of vehicles and buildings in the Galveston Beach area. Four numerical configurations were adopted to model coastal roads and an elevated building using a high-resolution LES technique. The parameter space of the problem was examined by varying the surge height, period, SL, and bathymetry using measurements and SLR prediction models. In total, 61 LESs were conducted to investigate the resiliency of vehicles and 9 simulations were run to examine the resiliency of a coastal building. Vehicle mobility criterion, exerted hydrodynamic forces, and BFE levels were employed in a novel way to evaluate the stability of vehicles and infrastructure during storm surge events.

In summary, the key findings of this study are as follows:

1. Infrastructure resilience strategies should account for the interacting effects of storm surge intensification and SLR together when calculating the flood and storm surge safety factors over the next 100 years.

2. SLR over the next decades will consistently increase the risk of all cases regardless of their storm surge height values or bathymetry. Some storm surge heights that are safe now will become unsafe in the future with an SLR.

3. The LESs reveal the importance of capturing the full storm surge wave-wave/structure interactions and resolving turbulence to achieve an accurate assessment of the coastal mitigation strategies.

4. Extreme storm surges are highly turbulent because of their speed. Our LES results indicate that the collision of fresh high-momentum waves that propagate toward the coast and the residual low-momentum waves that go back from the coast to the ocean increases this turbulence. Wave-bathymetry interactions and other surface heterogeneity elements can further increase the turbulent nature of these flows.

5. The high-resolution LESs can be employed to improve the coastal risk assessments in large-scale regional surge models such as SLOSH. These models can produce inaccurate storm surges near coastal areas due to their low resolution and simplification of the governing equations. When compared to the LES results, SLOSH outputs had some delays or discrepancies in the predicted surge levels. Coupling SLOSH with LES can improve surge forecasts, particularly near the shoreline. Advancing sub-grid scale parameterizations by accounting for wave-wave/turbulence/bathymetry interactions can further ameliorate the predictions in such models and lead to a better coastal risk assessment at a regional scale.

6. In the considered Galveston coastal road location,
   
   i. An SLR of ~1 m increases the danger level of the weakest considered wave (2 m high) for vehicles on the road by 36%–50% from its current value of <1%.
   
   ii. A 1 m elevation of the storm surge waves, with a fixed SL, could increase danger levels by ~54%.
   
   iii. The current mitigation strategy fails for wave heights greater than 3 m. We suggest building barrier walls or further elevation of the road to keep the road safe for vehicles in case of extreme storm surges.

1. Building NFIP codes and FEMA regulations should consider the following remarks:

   i. The distribution of hydrodynamic forces on buildings is nonlinear in all directions and can significantly exceed the calculations from classical theories that neglect turbulence effects. Moreover, stress levels experienced by the studied building increase non-linearly with wave height increase. Hence, high-resolution models that are capable of resolving turbulent eddies and fluid-structure interactions should be used to accurately predict stormwater loads.

   ii. In our considered cases, average inundation levels around the coastal building increase by ~1.5 m for every 2 m wave height elevation.
Our results demonstrate that many current mitigation strategies for coastal infrastructure resiliency will not be fully effective against hurricane intensification and SLR, and global climate change will force many mitigation plans to be reevaluated.

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