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Simulations of Hurricane Katrina (2005) under sea level and climate conditions for 1900

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Abstract Global warming may result in substantial sea level rise and more intense hurricanes over the next century, leading to more severe coastal flooding. Here, observed climate and sea level trends over the last century (c. 1900s to 2000s) are used to provide insight regarding future coastal inundation trends. The actual impacts of Hurricane Katrina (2005) in New Orleans are compared with the impacts of a similar hypothetical hurricane occurring c. 1900. Estimated regional sea level rise since 1900 of 0.75 m, which contains a dominant land subsidence contribution (0.57 m), serves as a ‘prototype’ for future climate-change induced sea level rise in other regions. Landform conditions c. 1900 were estimated by changing frictional resistance based on expected additional wetlands at lower sea levels. Surge simulations suggest that flood elevations would have been 15 to 60 % lower c. 1900 than the conditions observed in 2005. This drastic change suggests that significantly more flood damage occurred in 2005 than would have occurred if sea level and climate conditions had been like those c. 1900. We further show that, in New Orleans, sea level rise dominates surge-induced flooding changes,

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not only by increasing mean sea level, but also by leading to decreased wetland area. Together, these effects enable larger surges. Projecting forward, future global sea level changes of the magnitude examined here are expected to lead to increased flooding in coastal regions, even if the storm climate is unchanged. Such flooding increases in densely populated areas would presumably lead to more widespread destruction.

Abbreviations

GFDL	Geophysical Fluid Dynamics Laboratory
IPCC	Intergovernmental Panel on Climate Change
IPET	Interagency Performance Evaluation Taskforce
MSL	Mean sea level
SLR	Sea level rise
SST	Sea-surface temperature
USA	United States of America

1 Introduction

Tropical cyclones pose a significant natural threat to coastal communities, causing high surges, large waves, strong winds, and heavy precipitation. With increasing coastal populations, development, and infrastructure, the risk of damage from tropical cyclones is expected to increase, exacerbated by sea level rise (SLR) and possible climate-induced increases in tropical cyclone intensity. In this paper, we examine the influence of historical climate change and 20th century SLR on flooding in the populated, low-lying New Orleans area, Louisiana, USA. New Orleans is situated on the Mississippi River Delta (Fig. 1), along the northern Gulf of Mexico

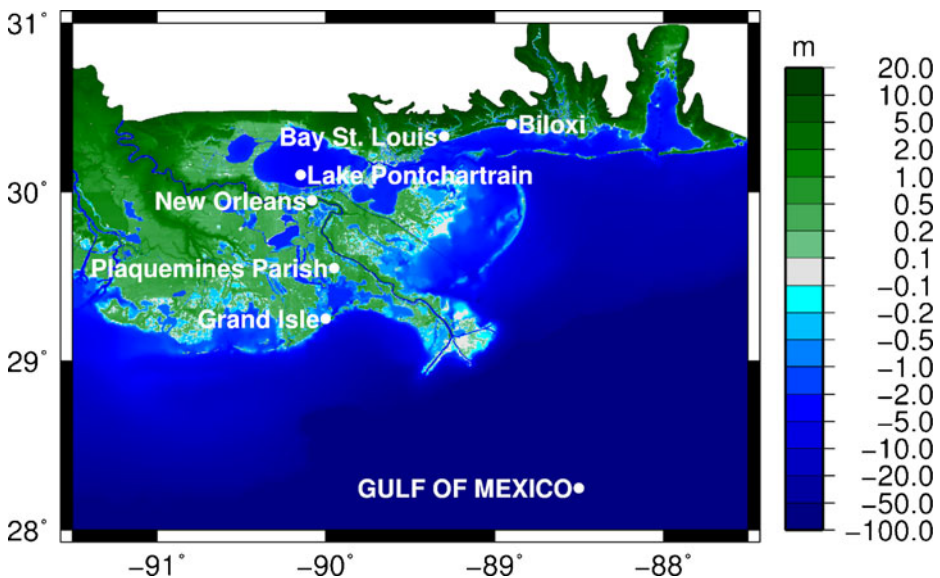


Fig. 1 Location map for greater New Orleans, Louisiana. Topography and bathymetry reflect current conditions in the 2000s, where elevations are shown in m above MSL_{2000s}

coastline. The City of New Orleans, its surrounding coastal Parishes, and communities in nearby coastal Mississippi are home to nearly one million people (2010 U.S. Census), and the region supports a wide array of industries including shipping, commercial fishing, oil and gas, and tourism. New Orleans is regularly exposed to severe hurricane events. In the last decade alone, New Orleans experienced high surges from Hurricanes Katrina, Rita, Gustav, Ike, and Isaac. The devastating 2005 event, Hurricane Katrina, which generated the highest surge on record in New Orleans (Travis 2005), is used here as the basis for evaluating coastal flooding by assuming hurricane scenarios similar to Hurricane Katrina, had this storm occurred at the turn of the last century, c. 1900.

In the following sections, we discuss historical climate and sea level trends, introduce the numerical simulation approach and hurricane scenarios, and present results and conclusions regarding changes in potential flood inundation over the last century.

2 Background

Global warming has the potential to increase coastal flooding, particularly in low-lying areas such as coastal Louisiana. The Intergovernmental Panel on Climate Change (IPCC 2007) reported an increase in the average global earth surface temperature of $0.76\text{ }^{\circ}\text{C}\pm 0.19\text{ }^{\circ}\text{C}$, between the periods of 1850–1899 and 2001–2005 (e.g., Hansen et al. 2001; Smith and Reynolds 2005); global sea-surface temperature (SST) over this same period was reported to rise $0.55\text{ }^{\circ}\text{C}\pm 0.16\text{ }^{\circ}\text{C}$ (e.g., Rayner et al. 2006; Smith and Reynolds 2005). There are two main mechanisms that potentially increase coastal flooding by a tropical cyclone as a consequence of global warming. Warmer SST leads to thermal expansion and glacier and ice-sheet melting, which increases eustatic, or global, sea levels (e.g., IPCC 2007; White et al. 2005), thereby increasing coastal flooding (e.g., Kleinosky et al. 2007; Smith et al. 2010). Second, greenhouse-gas-induced SST warming can contribute to increased tropical cyclone potential intensity (Emanuel 1987) that supports increased storm intensity (Elsner et al. 2008; Knutson and Tuleya 2004), and can lead to higher storm surge levels (e.g., Ali 1999; Lin et al. 2012; Mousavi et al. 2011). In this paper, the implications of tropical cyclone intensification and of sea level rise are considered.

2.1 Sea level rise over the last century

Several analyses of historical data quantified a global, or eustatic, SLR (ESLR) over the last century (e.g., IPCC 2007; White et al. 2005), with a reported ESLR of 1.7 to 1.8 mm/yr. We assume this historical rate represents the contribution of global climate change to New Orleans regional SLR, neglecting regional modulation of the global signal due to factors such as ocean circulation changes and gravitational effects of changing ice sheets. In the New Orleans area, local subsidence and soil compaction contribute substantially to relative sea level rise (RSLR), the sum of ESLR and local effects. Smith et al. (2010) summarized that local subsidence in the study area is due to a combination of glacio-isostatic subsidence, sediment compaction, and anthropogenic activity, including water and hydrocarbon extraction and construction of drainage systems, levees, among others. Several studies report significant subsidence and compaction over the last century in coastal Louisiana (e.g., Dixon et al. 2006). Syvitski et al. (2009) reported an average rate of subsidence of 5 to 6 mm/yr for the Mississippi River Delta. This suggests that RSLR in the study area over the last century is about 0.75 m, the sum of ESLR and subsidence and compaction. Here, we assume that this RSLR amount of 0.75 m applies to the New Orleans region, inclusive of coastal Mississippi.

2.2 Influence of global warming on hurricane intensity

As summarized in Knutson et al. (2010) and Mousavi et al. (2011), recent climatic research suggests that Atlantic hurricanes may intensify in response to long-term greenhouse-gas-induced warming (see also Knutson et al. 2013). Knutson and Tuleya (2004, 2008) used an idealized dynamical downscaling approach with the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model, a triply nested moveable-mesh hurricane prediction system, to simulate the influence of greenhouse-gas-induced warming on the intensity of hurricanes. They considered thermodynamic influences (SST changes and atmospheric temperature and moisture changes), and evaluated several convective parameterization options available in the GFDL hurricane model. Through these experiments, they estimated an average 8 % increase in tropical cyclone pressure differential (far-field less local barometric pressure) for every 1 °C of greenhouse-gas-induced tropical SST increase. Similarly, Knutson and Tuleya (2004, 2008) estimated a 3.7 % increase in hurricane wind speed for every 1 °C of tropical SST rise. This approximation for tropical cyclone intensification with greenhouse-gas-induced tropical SST warming neglects other meteorological influences such as wind shear—which can influence tropical system development into major hurricanes—but, the method attempts to include the influence of greenhouse warming on tropical lapse rates as discussed in Knutson and Tuleya (2004). The simplicity of this approximation, however, allows for an exploratory assessment of the influence of climate-change-induced SST warming on hurricane intensity and, thus, on flood inundation.

3 Methods

3.1 Hurricane and sea level scenario selection

In August 2005, Hurricane Katrina made landfall near New Orleans as a Category 3 hurricane. Storm surges in excess of 8 m were generated by this event (Resio and Westerink 2008), and are the highest in recorded U.S. history. Hurricane Katrina claimed the lives of more than 1800 people in Louisiana and neighboring Mississippi (Knabb et al. 2006), and caused widespread damage throughout the region, totaling more than \$149 billion in 2013 U.S. dollars (National Climatic Data 2013). Hereafter, the meteorological event of Hurricane Katrina, as it occurred in August 2005, will be referred to as ‘Historical Hurricane Katrina.’ The flood event of Historical Hurricane Katrina, as it occurred in August 2005 under present-day sea level, will be referred to as the ‘2005 Event’ (also Scenario 1).

To assess the relative influence of climate change along with local anthropogenic influences on SLR, scenarios were constructed to represent a storm like Hurricane Katrina should it have occurred at the turn of the last century, c. 1900. In selection of these scenarios, the following assumptions were made:

1. Mean SST rise in the Gulf of Mexico region since the late 1800 s is approximately 0.45 °C, based on a linear trend of 0.34 °C/100 yr in annual SSTs in the region over the period 1873–2005.
2. Mean ESLR over the last century is approximately 0.18 m, using the global mean sea level change as the adjustment.
3. Mean local SLR effects, in addition to the global, ESLR signal, in the study area over the last century give a RSLR of approximately 0.57 m.
4. Tropical cyclones a century ago were relatively less intense, due to the absence of 20th century greenhouse-gas-induced climate warming.

5. Tropical cyclone intensity as a function of tropical regional SST may be approximated as an 8 %/°C increase and 3.7 %/°C increase, respectively for barometric pressure and wind speed. By applying assumption 1, about one century ago, hurricane central pressure differential was 3.6 % less and wind speeds were 1.7 % weaker. The de-intensified meteorological event is hereafter called 'De-intensified Hurricane Katrina.' Application of Eq. 2 in our study implies that in addition to maximum intensity, the size of the storm also changes in the same sense for the hurricane. For the c. 1900 case, for example, the tangentially averaged surface wind speeds of our wind field (with 1.7 % reduction of intensity) have a radius of hurricane force winds that decreases from 0.1 % to 1.2 % depending on the time period examined. As noted in a previous idealized study with the GFDL (Geophysical Fluid Dynamics Laboratory) hurricane model (Knutson and Tuleya 1999), the radius of hurricane force winds in that model's climate warming experiments tends to increase along with the storm intensity. They noted an increase of about 2.5 % in radius of hurricane force winds corresponding to an overall storm intensity increase of 8 %. Using this same scaling implies an 0.5 % decrease in radius of hurricane force winds for a 1.7 % decrease in storm intensity, which generally supports the reduction in size used in our c. 1900 hurricane wind field.

Based on the above assumptions, six scenarios were identified to evaluate flooding characteristics: the 2005 event plus five modifications to the 2005 event that consider sea level trends and hurricane de-intensification:

1. (2005 event) Historical Hurricane Katrina (central pressure=920 mb and maximum wind speed=57 m s⁻¹) with present-day sea level (sea level=0.00 m, MSL_{2000s}).
2. Historical Hurricane Katrina with lower sea level, eustatic only (sea level=-0.18 m, MSL_{2000s}).
3. Historical Hurricane Katrina with lower sea level, eustatic and local (sea level=-0.75 m, MSL_{2000s}).
4. De-intensified Hurricane Katrina (central pressure=924 mb and maximum wind speed=56 m s⁻¹) with present-day sea level (sea level=0.00 m, MSL_{2000s}).
5. De-intensified Hurricane Katrina with lower sea level, eustatic only (sea level=-0.18 m, MSL_{2000s}).
6. De-intensified Hurricane Katrina with lower sea level, eustatic and local (sea level=-0.75 m, MSL_{2000s}).

Hereafter, these scenarios will be referred to using the above numeric identifiers.

3.2 Numerical simulation approach

The relevant processes contributing to flood levels and inundation extent during a hurricane are: surge generated by wind and by the inverse barometer effect (surge), setup induced by depth-induced wave breaking (wave setup), astronomical tides, and flooding from river discharge and precipitation. In this study, the analysis is simplified by considering flooding by surge and wave setup only.

An integrated numerical simulation approach was employed, which dynamically couples the hydrodynamic model ADCIRC (Luettich and Westerink 2004) with the full-plane spectral wave model STWAVE-FP (e.g., Smith 2007). ADCIRC solves the governing equations for conservation of mass and momentum; in application here, surface wind and barometric pressures provide input forcing while STWAVE-FP provides wave radiation stress forcing. STWAVE-FP solves the wave-action balance equation and simulates both wave transformation

and generation for waves in all directions (360°). Far-field wave generation for forcing STWAVE-FP at the offshore boundary was simulated with the deep-water spectral wave model WAM (Komen et al. 1994), which also solves the wave-action balance equation and additionally uses surface wind as forcing. Tight coupling between ADCIRC and STWAVE-FP is achieved by sharing of input wind forcing, water levels, currents, and wave radiation stress gradients between the two models at regular time steps throughout the simulation (Massey et al. 2011). This ADCIRC, STWAVE-FP, and WAM model setup has been validated for hurricane simulations in the study area (e.g., Bunya et al. 2010; Interagency Performance Evaluation Taskforce (IPET) 2008; Massey et al. 2011).

The reconstructed wind fields for the Historical Hurricane Katrina (Powell et al. 2010) were used as the basis for hurricane input forcing. These 3-hourly wind fields synthesized remote and in situ observations made during Hurricane Katrina's passage to produce a detailed, high-resolution wind field time series, H*Wind, for this storm. The surface pressure field generation is based on planetary boundary layer (PBL) methods following work by Thompson and Cardone (1996). The 3-hourly H*Wind interpolated to 15-min resolution using linear interpolation, where a moving-center approach is employed in order to preserve the bearing and range on a vortex-centered grid (Andrew Cox [Oceanweather Inc.], personal communications). Spatial interpolation is accomplished by spline interpolation between two consecutive H*Wind records. De-intensified Hurricane Katrina was developed by applying a 1.7 % and 3.6 % reduction respectively to the H*Wind and PBL products for Historical Hurricane Katrina; reducing the surface wind speed by the same fraction at all spatial locations; and increasing surface pressure by 4 mb at the storm center, with no change in pressure in the far-field environment surrounding the storm. There is very little discernable difference between the Historical Hurricane Katrina wind field and the De-intensified Hurricane Katrina wind field, which reflects the -1.7 % adjustment.

Sea level change induces landscape changes—specifically topographic and bathymetric elevation changes (e.g., FitzGerald et al. 2008) and land cover changes (e.g., Day et al. 2007). Sea level change was implemented within the model in two ways. First, we adopt a simplified approach to modifying bathymetry and topography. We assume a uniform lowering of the mean water surface throughout the computational domain to represent first-order changes in elevation, e.g., the so-called “bathtub” approach. While this modification reflects the influence of eustatic sea level change, this assumption is not strictly valid for local sea level change that impacts only a portion of the computational domain. However, changes in sea level made far away from the area of interest are not expected to significantly influence flood simulation results around New Orleans. Furthermore, this approach does not consider topographic changes induced by the coupled impact of changes in sediment supply and sea level, e.g., barrier island drowning and breakup with decreased sediment supply and SLR.

Second, we assume that sea level change induces land cover change, namely to the coastal wetlands. Vegetation serves to (1) increase frictional resistance within the water column and at the sea bottom and (2) decrease wind momentum transfer at the sea surface. Thus in the numerical models, frictional roughness values, land roughness length scales, and wind reduction values must be updated accordingly. We followed methods outlined in Atkinson et al. (2011). Spatially variable Manning's n coefficients were assigned to all model grids using land cover definitions from the United States Geological Survey (USGS) Gap Analysis Program (GAP) (Bunya et al. 2010; National Wetlands Research Center 2004). In Louisiana, the Manning's n coefficients range from 0.035 to 0.18. As sea levels increase, wetlands evolve from freshwater marsh to brackish marsh to open water. When vegetation changes are made, wind reduction factors are also modified for areas within 10 km upwind of vegetation changes.

Figure 2 shows the resulting bottom roughness, namely Manning's n , for the present-day and two alternate sea level conditions. In agreement with observed wetlands loss in southern Louisiana, roughly 4,900 km² since 1900 (e.g., Day et al. 2007), significant changes in bottom roughness are estimated under both the 0.18 m and 0.75 m of sea level lowering, because of increased land exposure. Most notable changes are in the regions fronting coastal Mississippi and offshore of Plaquemines Parish and Grand Isle; in the figure (right panes), an increase in Manning's n is seen by a conversion from dark to light blue, where land cover is converted from open ocean under present-day sea level to coastal wetlands for the two alternate 'historical' sea level conditions.

Finally, in order to understand how SLR and climate change impact the greater New Orleans area as it exists today, we assume no change in anthropogenic activity, such as infrastructure. Thus, all levees, roadways, and other manmade features that influence hydrodynamics are the same in all simulations. Numerical simulations were carried out for the six scenarios specifically to explore the relative roles of sea level change and climate-change-induced hurricane intensification on flooding in the study area.

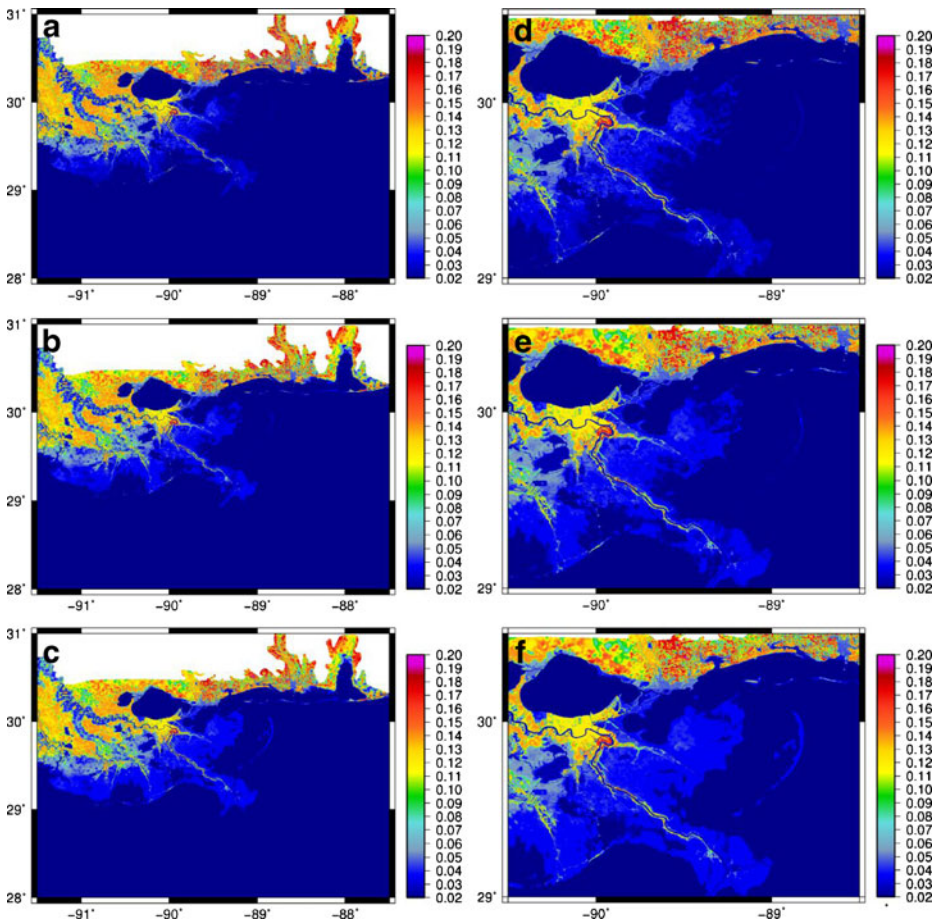


Fig. 2 Manning's n values used in ADCIRC simulations for (a and d) current sea level (MSL_{2000s}), (b and e) sea level that is 0.18 m lower than MSL_{2000s}, (c and f) sea level that is 0.75 m lower than MSL_{2000s}

4 Results and discussion

For the purposes of this discussion, we will use the following definitions:

- Flood elevation: water elevation above MSL_{2000s} , where MSL_{2000s} is MSL in the decade of the 2000s;
- Storm surge: water elevation above still-water line, as represented by the sea level condition considered; and
- Inundation extent: the lateral extent of flooding.

For example, if the simulation is carried out for a sea level lowering of 0.75 m, the still-water elevation for the simulation would be -0.75 m, MSL_{2000s} . Then, for a simulated flood elevation of 1.00 m, MSL_{2000s} , the storm surge would be 1.75 m (1.00 m minus -0.75 m).

Figure 3 shows maps of simulated flood elevation for the 2005 event and flood elevation differences (Scenario 1 minus the Scenario being compared), while Fig. 4 shows flood elevations across selected transects and Table 1 gives numeric flood elevation values and differences for selected locations. As anticipated, Fig. 3 (left panes; Scenarios 2 and 3) shows that Historical Hurricane Katrina simulated using lower sea level conditions yields flood elevations at nearly all locations that are lower than the 2005 event (Scenario 1). The inundation extents in areas west of Lake Pontchartrain and the low-lying areas west of Grand Isle are also measurably reduced (Figs. 3 and 4, transect b). In contrast, the inundation extent marginally changed along the Mississippi coast (Fig. 4, transects e and f), likely due to the extremely high surges associated with Hurricane Katrina and confining topographic conditions. Figure 3 (left panes) also shows that, with the exception of a few small areas, all modeled flood elevations during the 2005 event (Scenario 1) were higher by at least the sea level amount. During the 2005 event (Scenario 1), flood elevations were greater than the sea level change amount in the areas immediately to the east of the Mississippi River and southwest of Bay St. Louis; an example of this flood-elevation difference is displayed in red and orange on Fig. 3, pane c. This variation in flood elevation indicates that estimated 20th century SLR in these areas amplified Hurricane Katrina's storm surge by enabling surge to propagate more freely across areas with greater initial depths. Therefore, we conclude that the interaction between elevated sea level, as in the 2005 event (Scenario 1), and surge generation is highly complex and nonlinear in these areas.

The nonlinear coupling of surge generation and elevated sea levels is most apparent in the vicinity of maximum flood elevation during Hurricane Katrina, Bay St. Louis (Fig. 4, transect e and Table 1). Here, modeled flood elevations during the 2005 event (Scenario 1) are greater than those for Scenarios 2 (sea level 0.18 m lower) and 3 (sea level 0.75 m lower) by about 0.3 m (4 % of the modeled 2005 event's flood elevation) and 1.3 m (17 % of the modeled 2005 event's flood elevation), respectively. Here, the change in sea level makes up only about half of the increase in flood level. Our findings are consistent with Smith et al. (2010) who found that, in the vicinity of maximum flood elevation, SLR and the increase in surge contributed in nearly equal amounts to the flood elevation increase.

There are two factors that contribute to changes in surge generation with changes in mean sea level. First, the coupling of still-water depth and surge generation and propagation varies with specific storm condition and geographic setting. Second, the dramatic change in land cover south of the region of maximum surge during Hurricane Katrina (Fig. 2) appears to be the dominant factor in surge changes in our study area. While shallower water depths, as would be the case during a lower sea level condition, generally support more surge generation (e.g., Resio and Westerink 2008), the presence of vegetation generally impedes storm surge

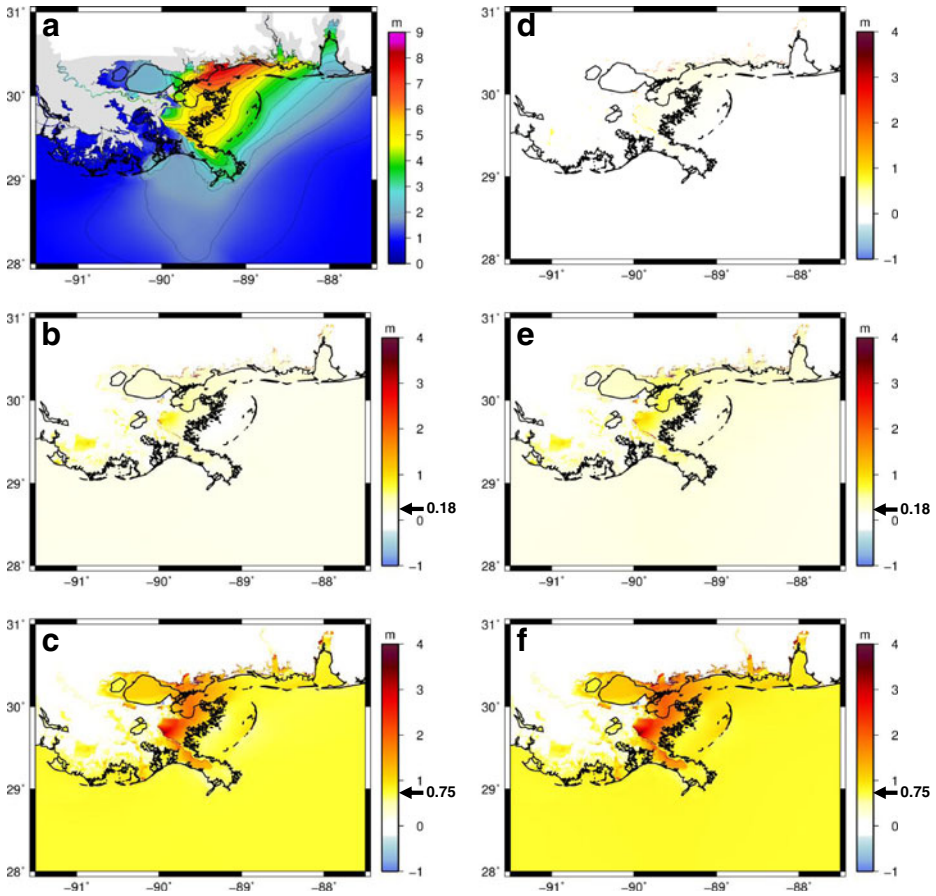


Fig. 3 Simulated differences in flood elevations, with respect to flood elevations for the 2005 event, namely Historical Hurricane Katrina and current sea level (MSL_{2000s}) (Scenario 1) (a). Differences are computed as the 2005 event simulation (Scenario 1) minus the alternate simulation: **b** Historical Hurricane Katrina but sea level that is 0.18 m lower than MSL_{2000s} (Scenario 1 minus Scenario 2), **c** Historical Hurricane Katrina but sea level that is 0.75 m lower than MSL_{2000s} (Scenario 1 minus Scenario 3), **d** De-intensified Hurricane Katrina and current sea level (MSL_{2000s}) (Scenario 1 minus Scenario 4), **e** De-intensified Hurricane Katrina and sea level that is 0.18 m lower than MSL_{2000s} (Scenario 1 minus Scenario 5), **f** De-intensified Hurricane Katrina and sea level that is 0.75 m lower than MSL_{2000s} (Scenario 1 minus Scenario 6). Flood elevations are shown in m, relative to MSL_{2000s}. Arrows next to the colorbars indicate the alternate sea level value for that simulation

propagation (e.g., Loder et al. 2009). In our case, the wetlands region south of Bay St. Louis is much more extensive in Scenarios 2 and 3 than it is in Scenario 1. This results in a substantial reduction in the amount of momentum imparted by the wind to the water column, as well as a substantial increase in momentum loss due to vegetative drag on the water.

The change in storm surge is even more dramatic along transects c and d in Fig. 4, which pass through and just south of the City of New Orleans. Here, the change in storm surge makes up as much as 75 % of the total decrease in flood elevation between the 2005 surge (Scenario 1) and Scenarios 2 (sea level 0.18 m lower) and 3 (sea level 0.75 m lower), where the total decrease in flood elevation is as much as 0.8 m (20 % of the modeled 2005 flood elevation) and 2.4 m (60 % of the modeled 2005 flood elevation), respectively.

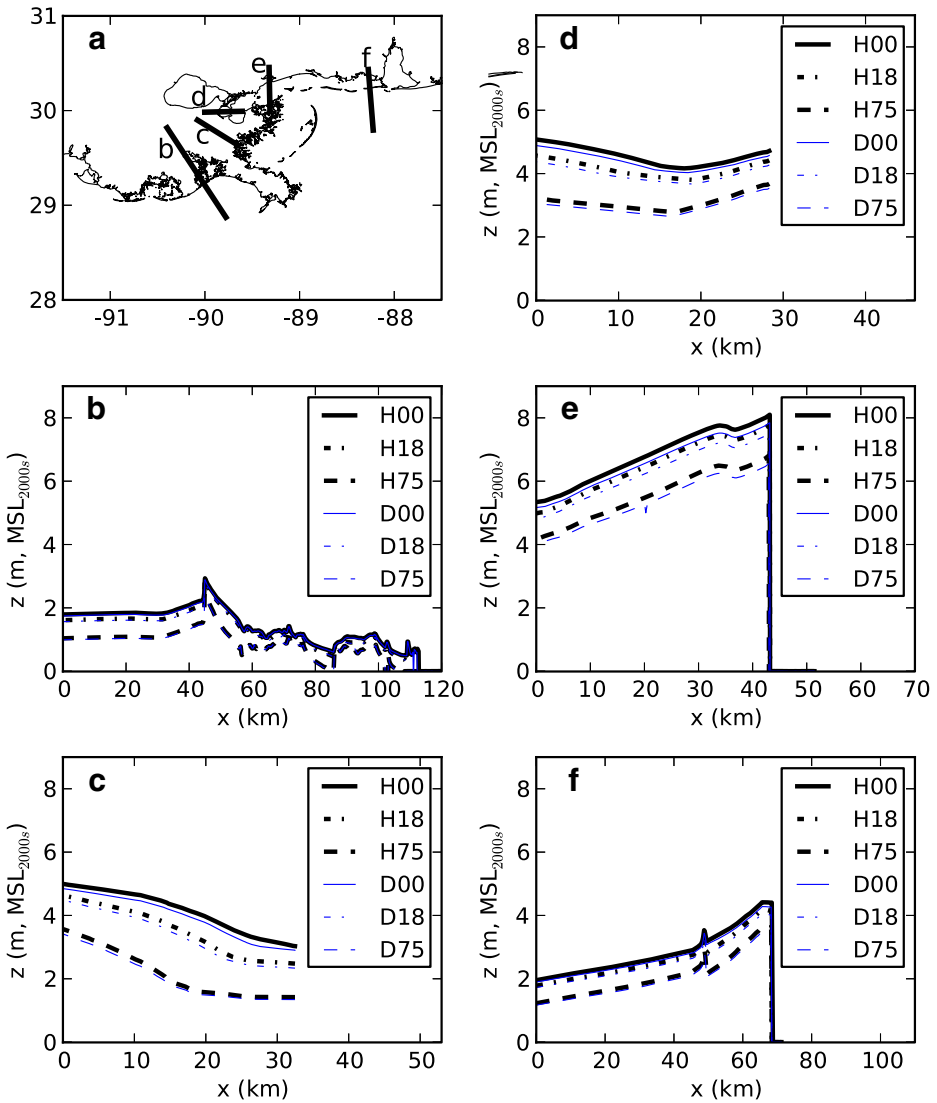


Fig. 4 Transects of simulated flood elevations at selected locations shown in (a). Legends are specified as H00 = Historical Hurricane Katrina with current sea level (MSL_{2000s}) (Scenario 1), H18 = Historical Hurricane Katrina but sea level that is 0.18 m lower than MSL_{2000s} (Scenario 2), H75 = Historical Hurricane Katrina but sea level that is 0.75 m lower than MSL_{2000s} (Scenario 3), D00 = De-intensified Hurricane Katrina and current sea level (MSL_{2000s}) (Scenario 4), D18 = De-intensified Hurricane Katrina and sea level that is 0.18 m lower than MSL_{2000s} (Scenario 5), D75 = De-intensified Hurricane Katrina and sea level that is 0.75 m lower than MSL_{2000s} (Scenario 6). Transects directions are oriented from offshore to onshore

By considering no change in sea level, but allowing for de-intensification of the hurricane (Scenario 4), it is seen that the 2005 event (Scenario 1) yields slightly higher modeled surges in much of the study region; in general, flood elevations from Historical Hurricane Katrina are 2 to 3 % higher than those from De-intensified Hurricane Katrina (pane d of Figs. 3 and 4, and Table 1).

Table 1 Hurricane Katrina maximum simulated flood elevations and flood elevation differences at selected locations. Flood elevation differences are calculated as the flood elevation for the 2005 historical simulation minus that for the alternate simulation, such that positive values indicate flood levels were higher during the 2005 historical event

Location	Scenario 1: Maximum flood elevation for historical intensity, current sea level (m, MSL _{2000s})	Scenario 2: Difference: historical intensity, sea level 0.18 m lower (m [%])	Scenario 3: Difference: historical intensity, sea level 0.75 m lower (m [%])	Scenario 4: Difference: de-intensified, current sea level (m [%])	Scenario 5: Difference: de-intensified, sea level 0.18 m lower (m [%])	Scenario 6: Difference: de-intensified, sea level 0.75 m lower (m [%])
Gulf of Mexico (location shown in Fig. 1)	0.98	0.18 [18 %]	0.75 [77 %]	0.02 [2 %]	0.20 [20 %]	0.77 [79 %]
Lake Pontchartrain (location shown in Fig. 1)	2.08	0.29 [14 %]	0.98 [47 %]	0.07 [3 %]	0.36 [17 %]	1.03 [50 %]
New Orleans, LA: 17th Street canal in vicinity of levee breach	2.82	0.22 [8 %]	0.77 [27 %]	0.08 [3 %]	0.30 [11 %]	0.87 [31 %]
New Orleans, LA: Lower 9th Ward in vicinity of levee breach on Inner Harbor Navigation Canal	4.24	0.09 [2 %]	0.74 [17 %]	0.04 [1 %]	0.21 [5 %]	0.88 [21 %]
Plaquemines Parish, LA East Bank	4.92	0.11 [2 %]	0.60 [12 %]	0.09 [2 %]	0.18 [4 %]	0.76 [15 %]
Grand Isle, LA	2.50	0.09 [4 %]	0.53 [21 %]	0.04 [2 %]	0.13 [5 %]	0.58 [23 %]
Bay St. Louis, MS	7.67	0.32 [4 %]	1.27 [17 %]	0.24 [3 %]	0.56 [7 %]	1.51 [20 %]
Biloxi, MS	6.48	0.19 [3 %]	0.80 [12 %]	0.20 [3 %]	0.40 [6 %]	1.04 [16 %]

When De-intensified Hurricane Katrina is combined with lower sea levels, the relative impact of sea level on surge generation is again made clear (Fig. 3, right panes). Scenario 6 (de-intensified with sea level 0.75 m lower) yields the most dramatic decrease in flood elevations, with respect to the 2005 event (Scenario 1). However, when comparing Scenario 3 (Historical Hurricane Katrina with sea level 0.75 m lower) with Scenario 6, the increase in surge contribution from intensification alone remains on the order of 2 to 3 %. Transects d and e (Fig. 4), through New Orleans and Bay St. Louis, show that the difference between the more intense and less intense storms is roughly constant, regardless of the sea level scenario considered.

In summary, the combination of 0.75 m of relative SLR and a slight intensification of hurricane conditions gave rise to substantially higher flood elevations in greater New Orleans in 2005 than would have occurred c. 1900. By comparing the 2005 event (Scenario 1) with the de-intensified case with sea level lower by 0.75 m (Scenario 6), we estimate that modeled flood elevations during the 2005 event were at least 0.75 m higher in most locations than they would have been had the storm hypothetically occurred at the turn of the last century. Furthermore, from the City of New Orleans to Biloxi, the simulated flood elevation change is substantially higher than the estimated historical SLR of 0.75 m (Table 1 and Fig. 3). For example, in Bay St. Louis we estimate that flood elevations were 1.5 m (20 %) higher in the 2005 event than they would have been if the storm had occurred c. 1900; here, half of the increase is due to SLR while the other half is mostly due to an increase in surge from other related indirect effects. In the City of New Orleans, in the vicinity of levee failures along the 17th Street and Inner Harbor Navigation Canals, flood elevations were about 0.9 m higher in 2005 than they would have been c. 1900, according to our simulations.

4.1 Implications for New Orleans

The RSLR (including associated decreases in wetlands area) along with a small potential hurricane intensification estimated for the study area over the last century together gave rise to a significant increase in vulnerability to hurricane flooding in our simulations. In 2005, extensive levee failures in New Orleans devastated the city. In neighboring Mississippi, extreme flooding and waves extended as far inland as Interstate 10, completely destroying homes, businesses, roadways, and other critical infrastructure. Hurricane flood damages are primarily related to flood depth and wave loading, such that a small increase in flood depth, on the order of 0.15 m, can substantially increase damages (e.g., Federal Emergency Management Agency 2009). In coastal Mississippi, particularly in the vicinity of Bay St. Louis, it is likely that a reduction in flooding on the order of 1.0 to 1.5 m would have resulted in significantly less damage in the area.

In the City of New Orleans, 50 levee failures occurred (IPET 2008). Here, we estimate flood levels would have been on the order of 0.9 m lower in some of the canals, if the storm had occurred on a lower (c. 1900) sea level and had been slightly less intense. It is possible that such a measurable decrease in surge would have reduced the hydrodynamic loading on the levees. For example, the 17th Street canal breach, near Lake Pontchartrain, occurred at 5 am local time on August 29th, 2005 when flood elevation in the canal was about 2.1 m, MSL_{2000s} ; peak observed elevations of about 2.4¹ m, MSL_{2000s} occurred between 9 and 10 am (IPET 2008). If flood elevations were reduced on the order of 0.9 m at this location, the peak flood

¹ Peak flood elevation at the levee breach was estimated based on a reported 3.3 m, NAVD88 high water mark elevation at the 17th Street canal entrance (IPET 2008) less an estimated amount of 0.9 m to account for water level drop in the canal due to debris build up at the bridge at the canal entrance (IPET 2008). We neglected the difference between MSL_{2000s} and NAVD88; this difference is 0.011 m, based on National Geodetic Survey (2013) CO-OPS/NGS Elevation Data. PID BJ1342. Note that the ADCIRC simulations herein do not include the impact of debris build up at the bridge, thus the relatively higher simulated value in Table 1 for the 17th Street canal.

elevation would have been about 1.5 m, MSL_{2000s} —roughly 0.5 m below the 2.1-m elevation at failure.

5 Summary and conclusions

By looking back in time, we explore the implications for storm surge given a century of RSLR (including wetlands loss) in the New Orleans area and an estimate of Atlantic hurricane intensification due to climate warming. We estimate that the historical changes have had a significant impact on coastal flood potential in greater New Orleans. In our simulations, the flood elevations during Hurricane Katrina in 2005 were estimated to be 15 to 60 % higher in coastal areas because of SLR (with associated wetlands loss) and hurricane intensification estimated for the past century. Consequently, we infer that the amount and extent of damage would have been less severe had Hurricane Katrina taken place under c. 1900 climate and sea level conditions. We also demonstrate that in terms of surge generation, the influence of SLR (including wetlands loss) is much more significant than climate-change induced hurricane intensification. The end result is that slight changes in hurricane intensity along with substantial (0.75 m) SLR give rise to large changes in surges in some locations.

Yet, the relationship between surge generation and propagation and SLR is complex. Here, we show that changes in land cover have the potential to significantly influence the surge response; for Hurricane Katrina, its influence was significant along the Mississippi coast. In our analysis, we made several simplifying assumptions. Other than drowning in place, we assumed no changes in bathymetry or topography with SLR, and we adopted a simplified model for evaluating land cover change. We speculate that processes such as barrier-island degradation would further enhance surges along the Mississippi coast.

Looking forward, it is critically important that we understand future coastal flooding vulnerability and risk. The Hurricane Katrina example shown here provides some insight regarding the increases in coastal storm flood risk facing other coastal cities around the globe in the coming century and beyond. ESLR projections for 2100 are in the range of the relative rates realized in New Orleans over the last century, 0.75 m. Although the net effect of storm climate changes (e.g., changes in frequency, intensity and track) remain uncertain, we conclude that SLR increases the risk of coastal flooding from storm surges, and that depending on the setting, the increases in flood elevation for a given storm may greatly exceed the SLR for that region. Future flood level increases would presumably lead to wider spread destruction, which in turn may lead to more pronounced global economic and community impacts.

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