Title

Future projections of storm surge in Hurricane Katrina and sensitivity to meteorological forcing resolution

Journal

Environmental Research Communications, 6(9)

ISSN

2515-7620

Authors

Danso, Derrick K
Patricola, Christina M

Publication Date

2024-09-01

DOI

10.1088/2515-7620/ad7351

PAPER • OPEN ACCESS

Future projections of storm surge in Hurricane Katrina and sensitivity to meteorological forcing resolution

To cite this article: Derrick K Danso and Christina M Patricola 2024 *Environ. Res. Commun.* **6** 095018

IOP Publishing Environ. Res. Commun. 6 (2024) 095018 https://doi.org/10.1088/2515-7620/ad7351

Environmental Research Communications

OPEN ACCESS

RECEIVED
30 May 2024

REVISED
16 August 2024

ACCEPTED FOR PUBLICATION
23 August 2024

PUBLISHED
17 September 2024

PAPER

Future projections of storm surge in Hurricane Katrina and sensitivity to meteorological forcing resolution

Derrick K Danso[1,*] and **Christina M Patricola**[1,2]

[1] Department of the Earth, Atmosphere and Climate, Iowa State University, Ames, United States of America
[2] Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: ddanso@iastate.edu and cmp28@iastate.edu

Keywords: storm surge, Hurricane Katrina, climate change, ADCIRC, meteorological forcing, horizontal resolution

Supplementary material for this article is available online

Abstract

In this study, we investigated whether and how the storm surge induced by Hurricane Katrina could change if it occurs in a future warmer climate, and the sensitivity of the changes to atmospheric forcing resolution. Climate model simulations of Hurricane Katrina at 27 km, 4.5 km, and 3 km resolutions were used to drive storm surge simulations in historical and future climates using the ADvanced CIRCulation (ADCIRC) model. We found that peak surge height increased significantly in the future with all forcing resolutions. However, the future projection is 22% greater in the 3 km forcing, typical of regional climate models, compared to the 27 km forcing, typical of state-of-the-art global climate models. Additionally, the spatial extent of the future change is highly sensitive to forcing resolution, extending most broadly under the 27 km forcing. Furthermore, we found that storm surge duration decreases in the future with all forcing resolutions due to increasing TC translation speed and decreasing ocean lifetime. However, the future change in the surge duration is sensitive to the forcing resolution, decreasing by 31% in the 27 km forcing and 6% in the 3 km forcing.

1. Introduction

One of the major hazards of landfalling tropical cyclones (TCs) to coastal communities is storm surges. Storm surges cause coastal inundation and flooding, which lead to loss of life and destruction of infrastructure. For example, in 2005, Hurricane Katrina affected several coastal regions in the US along the Gulf of Mexico and caused over 1,800 fatalities and more than $100 billion in property damages (Knabb *et al* 2005, Kates *et al* 2006). A significant portion of the damages caused by Hurricane Katrina were directly linked to storm surge and its associated coastal inundation (Rappaport 2014). Storm surges are also estimated to cause almost half of fatalities associated with TCs (Rappaport 2014).

Although storm surge depends on the geophysical characteristics of the impacted area, such as the bathymetry and coastline geometry (Rego and Li 2010, Weaver and Slinn 2010, Mayo *et al* 2014, Akbar *et al* 2017), it is strongly driven by storm characteristics including intensity, size, and translation speed (Zhong *et al* 2010, Needham and Keim 2014, Sebastian *et al* 2014, Thomas *et al* 2019). Therefore, reliable storm surge predictions require accurate information about storm characteristics. Climate model projections show that some of these storm characteristics will change in the future (e.g., Knutson *et al* 2010, Bacmeister *et al* 2018, Bhatia *et al* 2018, Patricola and Wehner 2018). Specifically, there is medium-to-high confidence that the global average intensity of TCs will increase in the future due to global warming (Knutson *et al* 2020). This will likely impact future storm surges even before considering the compound effects of sea level rise.

Hurricane wind and pressure fields are used as meteorological forcing inputs for storm surge models to estimate coastal inundation (Cardone and Cox 2009, Dube *et al* 2009, Dietrich *et al* 2012). These fields are usually obtained from observed and simulated hurricane data. For instance, Fossell *et al* (2017) used best track data as meteorological forcing for a hydrodynamic coastal surge model to investigate the sensitivity of inundation forecasts to errors in hurricane parameters by adding systematically generated perturbations to them. Their results showed that errors in TC tracks and intensity limit the practical predictability of storm surge inundation. Similarly, Kowaleski *et al* (2020) used a storm surge model to simulate coastal inundation using hurricane wind and pressure fields from a regional climate model as meteorological forcing. They showed that a shorter lead time in the atmospheric forcing input provides higher confidence in inundation predictions.

To investigate how global warming will influence storm surge risk, hindcasted (historical) and projected (future) TC wind and pressure fields can be used as forcing inputs to storm surge models. The simulated changes in inundation can then be determined. As done in many previous studies, a common approach to provide both historical and future TC information is to use regional (RCM) or global climate model (GCM) simulations as forcing inputs (Marsooli *et al* 2019, Mori *et al* 2019, Camelo *et al* 2020, Shimura *et al* 2022, Ayyad *et al* 2023, Salarieh *et al* 2023). The horizontal resolutions of the forcing inputs usually differ among the various studies and models. Forcing resolutions based on recent studies have ranged from 4 km or finer (e.g., Camelo *et al* 2020) to coarser resolutions of at least 60 km (e.g., Mori *et al* 2019).

Horizontal resolutions of ~0.25° or finer are usually considered TC-permitting in high-resolution numerical models (e.g., Patricola *et al* 2017, Roberts *et al* 2020, Fu *et al* 2021, Li *et al* 2023). Similar resolutions are sufficient for the large-scale modeling of TC surges (Bloemendaal *et al* 2019). However, TC characteristics such as wind speed and central pressure, two of the main drivers of storm surge, are highly sensitive to horizontal resolution at TC-permitting scales (Jin *et al* 2014; Davis, 2018; Patricola and Wehner 2018). Consequently, simulated storm surge and its characteristics may be sensitive to the horizontal resolution of meteorological forcing input used for storm surge models. Generally, finer horizontal resolutions produce stronger and more realistic TC intensity compared to coarser resolutions (Davis 2018, Roberts *et al* 2020). Based on this, it is expected that TC wind and pressure fields based on typical convection permitting RCM resolutions (4 km or finer) will produce stronger storm surges than fields based on most common and publicly available currently high-resolution GCMs with resolutions around 25 km. Examples of such GCMs are those included in the High-Resolution Model Intercomparison Project (HighResMIP) (Haarsma *et al* 2016). However, it is unclear how much the magnitude of storm surges produced by forcings at typical RCM resolutions will differ from those produced by typical GCM resolutions. This is further complicated by the response of TC intensity to climate change. While TC intensity increases in response to warmer conditions in climate models, the change may not necessarily be equal when comparing the responses at different horizontal resolutions for the same model. Additionally, other surge characteristics, such as the duration, are also influenced by the intensity of storm surges and are thus likely sensitive to the horizontal resolution of atmospheric forcing. However, there are currently no studies quantifying such differences.

Therefore, the goal of this study is to use meteorological forcings of different resolutions to investigate whether and how the storm surge caused by Hurricane Katrina will change if a similar event occurs in a future warmer climate. The novelty and main contribution of this study are to both project Katrina's future storm surge characteristics, including the peak surge height and surge duration, and to quantify their potential sensitivity to meteorological forcing resolutions typical of RCMs and state-of-the-art GCMs. We made storm surge hindcasts of Hurricane Katrina using meteorological forcings of different horizontal resolutions as inputs to the ADvanced CIRCulation (ADCIRC) model (Luettich *et al* 1992). We then used the pseudo-global warming approach to investigate whether and how Hurricane Katrina's surge, including peak surge height and duration, would change if it occurred in a future warmer climate.

2. Materials and methods

2.1. Storyline hurricane simulations

Sea level pressure (SLP) and wind fields for Hurricane Katrina in historical and future climates were used as meteorological forcing inputs to the ADCIRC model. These fields were produced from Weather Research and Forecasting (WRF) model simulations (Patricola and Wehner 2018). The National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) Reanalysis (Saha *et al* 2010) provided initial and lateral boundary conditions for the historical WRF model hindcasts of Hurricane Katrina, which covered the period from 27 to 31 August 2005 at 00 UTC. After verifying that the hindcast was realistic by comparing the simulated TC tracks and intensity to those of observations, the historical boundary conditions were then perturbed by adding an anthropogenic climate change signal to perform experiments representing Hurricane Katrina if it were to occur at the end of the 21st century, using the pseudo-global warming (Schär *et al* 1996) or 'storyline' approach. The climate change perturbation for the end of the 21st century was based on simulations from the Community Climate System Model (CCSM4) under the Representative Concentration Pathway (RCP) 8.5 scenario of the Coupled Model Intercomparison Project Phase 5 (CMIP5).

In both the historical and future climates, simulations were performed using three horizontal resolutions (i.e., 27 km, 4.5 km, and 3 km). This makes the simulations suitable for investigating the sensitivity of simulated storm surges to the horizontal resolution of meteorological forcing at TC-permitting scales. In the 27 km simulations, convection was parameterized, while the 3 km and 4.5 km simulations were convection-permitting. Ten ensemble members were produced in both the historical and future simulations. In addition, the simulated fields were output at three-hourly time steps. The simulated TC coordinates were determined using the location of the minimum SLP. Further details about the simulations, including the evaluation of the historical hindcast, are presented in Patricola and Wehner (2018).

2.2. Storm surge model

We performed storm surge simulations with the two-dimensional (2D) depth-integrated ADCIRC model version 55. The ADCIRC model is a hydrodynamic circulation model that solves a modified form of the shallow water equations. It uses the finite element method to model the equations in space. Therefore, it can be run using highly flexible unstructured meshes. Such flexibility provides computational efficiency in coastal hydrodynamic modeling applications where finer spatial resolution is desired near the coast than in the deeper ocean. The ADCIRC model can accurately represent water elevations and wind-driven currents and has undergone extensive validation for many applications, including real-time TC-induced surge operations in various coastal regions across the world (e.g., Butler *et al* (2012), Colle *et al* (2008), Deb and Ferreira (2018), Dietrich *et al* (2010), Fleming *et al* (2008), Lin *et al* (2012), Westerink *et al* (2008)).

The ADCIRC mesh used in this study is the Hurricane Surge On-demand Forecast System (HSOFS) mesh, which was developed by AECOM, Riverside Technology, and the National Ocean Service (NOS) (Riverside Technology and AECOM 2015). The HSOFS mesh consists of ∼2 million nodes and ∼3.5 million triangular elements, covering the entire Gulf of Mexico and extending into the Atlantic Ocean to the approximate longitude of 65°W (Supporting Information figure S1). Additionally, the mesh extends to all overland areas of the US coast up to an elevation of 10 m above mean sea level (MSL), with a resolution as small as 200m in nearshore areas, which allows the model to resolve many aspects of inundation such as land surface heterogeneities. Further details can be found in Riverside Technology and AECOM (2015).

2.3. Storyline storm surge simulations

To simulate storm surge, tides in ADCIRC are generated by applying tidal forcing at the open ocean boundaries of the mesh using the eight major tidal constituents from the TPXO9 tidal atlas (Egbert and Erofeeva 2002). A model time step of 2 s was used for the simulations. Before the meteorological forcing is applied, a 20-day spinup period is first simulated to allow the model state to come to equilibrium. After the spinup period, a control simulation is made for the period covered by the WRF simulation of Hurricane Katrina (i.e., 27 to 31 August 2005). The control simulation did not include meteorological forcing but only tidal forcing. Thus, the control simulation represents the simulated tides. The maximum water elevation for the control simulation is shown in Supporting Information figure S2.

The hindcasted SLP and 10-m wind fields at 27 km, 4.5 km, and 3 km horizontal resolution were then used to force the ADCIRC model to simulate the historical surge caused by Hurricane Katrina. To verify the accuracy of the storm surge hindcasts, we compared the simulated total water elevation time series to observations from two National Oceanic and Atmospheric Administration tide gauges. The comparison reveals that the ADCIRC simulation reasonably reproduces the observed total water levels (figure S3). We then made simulations with the ADCIRC model to represent the storm surge caused by Hurricane Katrina if it occurred at the end of the century in warmer conditions using the SLP and 10-m wind fields based on the RCP8.5 scenario. Ten-member ensembles were performed for each forcing horizontal resolution in the ADCIRC simulations. Outputs from the ADCIRC model simulations were saved at 30-minute intervals.

Two metrics are used in our analysis of storm surge inundation risk. ADCIRC produces a global maximum water elevation file for each simulation. This file contains the peak water elevations at each node during the simulation period. Thus, the maximum storm surge is determined by subtracting the maximum water elevation at each node in the control simulation from the historical and future simulations. We then investigated the duration of storm surge at each node. First, surge (S) is computed as:

$$S_{t,n} = E_{t,n} - T_{t,n}$$

Where E and T are the simulated total water elevation and predicted high tide respectively, at time step t and node n. To estimate the duration, only $S \geqslant 1$ m is considered. This approximately corresponds to the current operational warning threshold of the National Hurricane Center (3 ft.) for coastal flooding. Surge duration is then defined simply as the length of time with at least 1m surge at each node expressed in days.

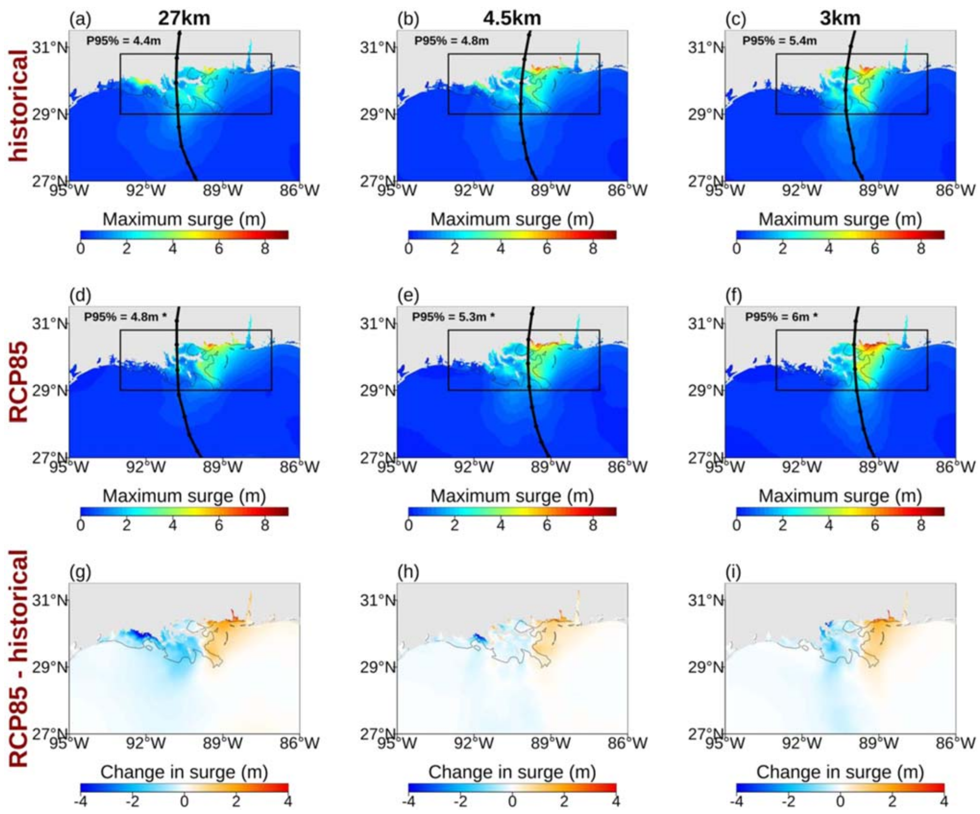

Figure 1. Ensemble mean peak surge heights (m) for the (a)–(c) historical and (d)–(f) future surge simulations for Hurricane Katrina, and (g)–(i) the change between the two periods (future minus historical) for the 27 km, 4.5 km and 3 km forcings. The black lines represent the simulated TC track. Peak surge is further computed within the subregion denoted by the black box. The * on the second-row subplots indicates a statistically significant ($p < 0.01$) change from the historical to the future climate within the black box.

3. Results

3.1. Peak storm surge

As expected, the simulated storm surge is sensitive to the horizontal resolution of atmospheric forcing (figure 1). While the spatial distribution of peak surge heights (henceforth S_{peak}) is similar across all resolutions in the historical period (figures 1(a)–(c)), the magnitude of S_{peak} is lowest with the 27 km forcing and highest in the 3 km. The S_{peak} increases for all resolutions in the future (figures 1(d)–(f)). Thus, the horizontal resolution of atmospheric forcing will not change the sign of projected storm surge. The magnitude of S_{peak} in the future remains lowest in the 27 km forcing and highest in the 3 km forcing.

To quantify the differences in the magnitude of simulated storm surge based on the three resolutions, we further investigated the S_{peak} over the subregion denoted by the black box in figures 1(a)–(f), given that it is where the highest surge values occur. It should be noted that this subregion has both offshore and onshore nodes, although much of the surge within it is offshore and would not necessarily contribute to the inundation in the coastal areas. However, the largest values of S_{peak} occur over typically dry areas onshore. Therefore, we compared the 95th percentile of S_{peak} values within the selected subregion. In the historical period, the 95th percentiles of S_{peak} are 4.4, 4.8, and 5.4 m for the 27, 4.5, and 3 km forcings, respectively. These values represent the least peak surge in 5% of all nodes within the subregion. However, this is not necessarily equivalent to 5% of the total area of the subregion, as the node lengths may vary. In the future climate, the 95th percentile increases by 9.1%, 10.4%, and 11.1% relative to the historical period for the 27, 4.5, and 3 km forcings, respectively. This represents a future projection that is 22% higher in the 3 km forcing compared to the 27 km forcing. In each case, the increase from the historical to future period was statistically significant ($p < 0.05$). Moreover, we found that the difference in peak surge height between the 3 km and 27 km forcings within the selected subregion is statistically significant ($p < 0.05$), whether in the historical or future climates.

The change between the future and historical climates shows an increase in S_{peak} to the east of the TC track and a decrease to the west across all three resolutions (figures 1(g)–(i)). This is attributed to the counterclockwise motion of TC winds, which forces water toward the coastline on the eastern side of the TC track and away from the western side. Furthermore, the change is larger and covers a broader spatial extent in the 27 km forcing. The

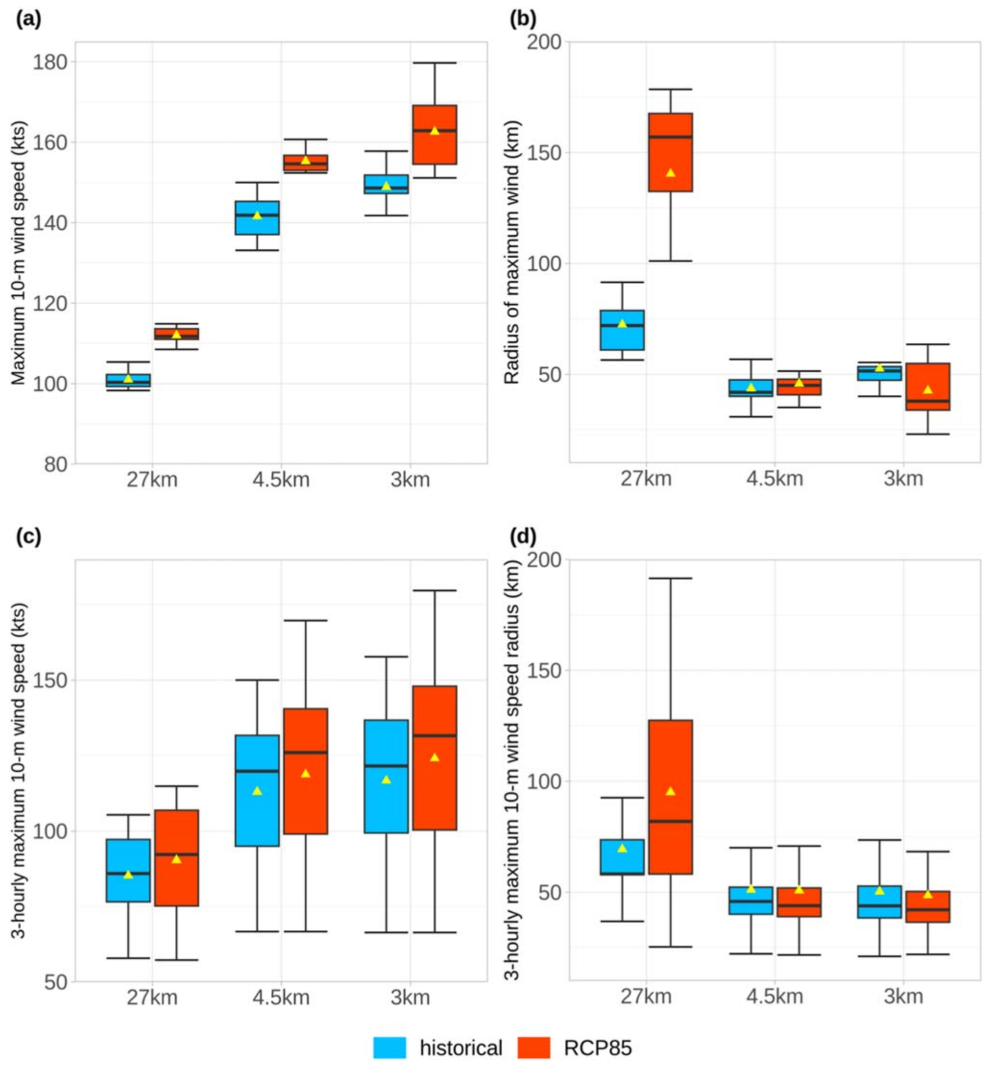

Figure 2. Simulated (a) peak 10-m wind speed (knots) and (b) radius of maximum wind (km) during the TC lifetime and (c) maximum sustained 10-m wind speed and (d) radius of maximum wind during the TC lifetime over the ocean across all ensembles for the historical and future periods for all three horizontal resolutions. The yellow triangle represents the ensemble mean values.

results presented in figure 1 indicate that the magnitude of both the simulated storm surge and its future changes are sensitive to the horizontal resolution of the driving meteorological forcing.

The lower magnitude of S_{peak} produced by the 27 km forcing in the historical simulation can be largely linked to the intensity of the simulated TC, defined here as the peak 10-m wind speed during the TC lifetime. Figure 2(a) shows the peak 10-m wind speed during the TC lifetime over all ten ensembles. In the historical period, the peak TC intensity is lowest in the 27 km resolution, with an ensemble mean (yellow triangle) of 101 kts, 142 kts, and 149 kts for the 27 km, 4.5 km, and 3 km forcings, respectively. For all three resolutions, the TC becomes more intense in the future climate, with the ensemble mean wind speeds increasing by 10.8%, 9.7%, and 9.2% for the 27 km, 4.5 km, and 3 km forcings, respectively. It is interesting to note that the percentage increase in the TC intensity is similar to the percentage increase in S_{peak}. Since storm surge is driven by the TC winds on the ocean, we further compared the maximum sustained wind speeds at all time steps of the TC's lifetime on the ocean across all ten ensembles and found a similar result (figure 2(c)).

To explain the differences among the three resolutions for the change in S_{peak} between historical and future climates (figures 1(g)–(i)), we examined the radius of the maximum wind (RMW) of the simulated TCs across all ten ensembles (figure 2(b)). From the historical to the future period, the ensemble mean RMW remains similar in the 4.5 km forcing and decreases in the 3 km forcing, with a percentage change of 4.9% and −18.8%, respectively. In contrast, the RMW almost doubles (93.8%) in the 27 km forcing, likely indicating that the 27 km resolution, while capable of representing a TC overall, may be less suitable for representing more localized features such as RMW. In addition to the peak 10-m wind speed increase, the doubling of RMW in 27 km forcing could explain the larger change in S_{peak} between the historical and future simulations compared to the 3 km and

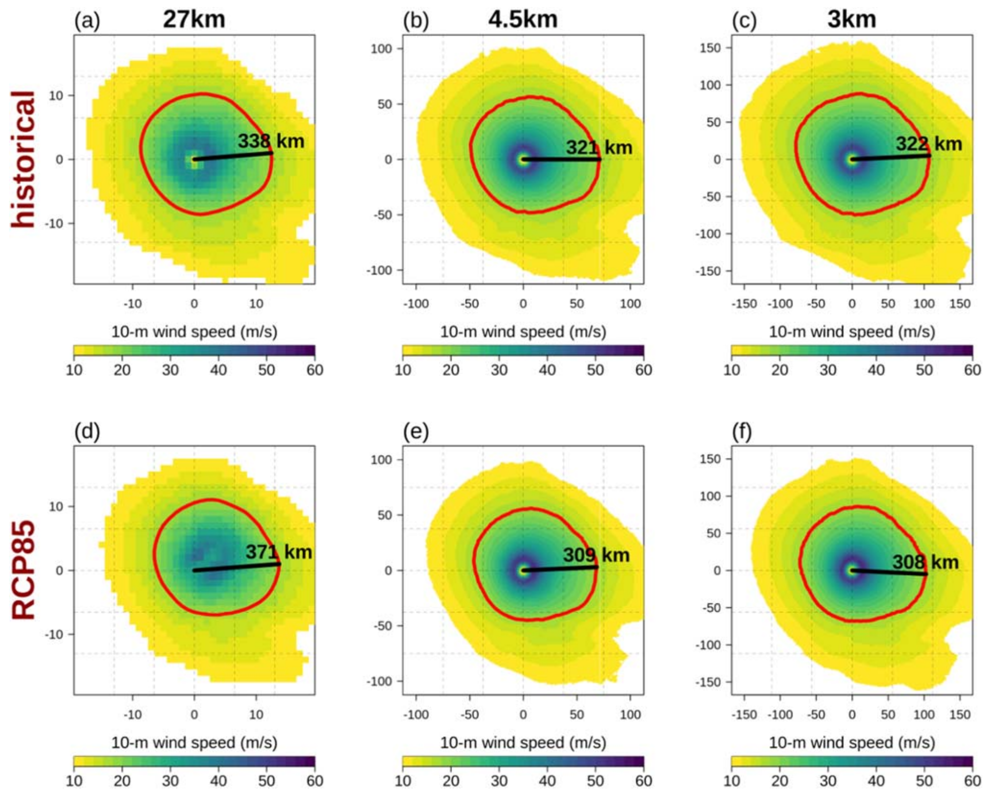

Figure 3. Ensemble mean 10-m wind speed (m/s) relative to TC center from a radius of 500 km averaged over all time steps during the entire TC life over the ocean. The red line represents the 18 m s^{-1} contour. The black line represents the distance from the TC center to the furthest point with 18 m s^{-1} within a 500 km radius.

4.5 km forcings. This result is similar to comparing the radius of the three-hourly maximum sustained wind speeds at all time steps of the TC's lifetime on the ocean across all ten ensembles (figure 2(d)).

The RMW change cannot explain the broader spatial extent of the future storm surge change in the simulations with 27 km forcing. This is because the peak 10-m wind speeds are much lower in the 27 km compared to the 4.5 km or 3 km, as shown in figure 2(a). Thus, to further explain this difference, we compared the TC size, defined here as the distance from the TC center to the furthest point with a wind speed of 18 m s^{-1} within a 500 km radius (figure 3). From the historical to future periods, the TC size slightly decreases for the 3 km (322 km to 308 km) and 4.5 km (321 km to 309 km) resolutions. In contrast, the TC size increases from the historical (338 km) to the future period (371 km) in the 27 km forcing. Thus, the region affected by the 27 km TC winds is larger in the warmer climate, which explains the broader extent of S_{peak} change between the historical and future periods. As shown by Davis *et al* (2010), who also found that coarser resolution overpredicted the extent of winds compared to finer resolution, the larger TC size in the 27 km simulation could be due to anomalously strong large scale surface winds that favor a particular quadrant of the TC. They attributed this to an extension of the 18 m/s radius beyond what would reasonably be considered the TC circulation. Similar findings have been shown in other studies (e.g., Sun *et al* (2013)). Other TC characteristics, such as the forward speed and angle of approach, can also influence storm surge (Pandey and Rao 2019, Zhang and Li 2019), although these were not investigated in this study. Thus, changes in such characteristics and their interaction with TC intensity and RMW changes can further influence future S_{peak} changes.

3.2. Storm surge duration

The duration of storm surge can be an important measure in determining the risk of extended flooding in coastal communities. Here, we compared the surge duration estimated from the simulated water elevations at each node of the ADCIRC mesh and for each of the meteorological forcing resolutions (figure 4). In the historical period, the magnitude of surge duration appears to be similar among the three resolutions (figures 4(a)–(c)), although there are slight differences in their spatial distributions. Thus, it may appear that meteorological forcing resolution does not influence the surge duration in the historical period. In the subregion denoted by the black rectangle, we found that the average surge duration across all ensembles is 0.13, 0.11, and 0.14 days for the 27, 4.5, and 3 km forcings respectively. Therefore, there is little sensitivity to the horizontal resolution for the surge duration in the historical average between 3 km and 27 km. Given that these values are based on the entire

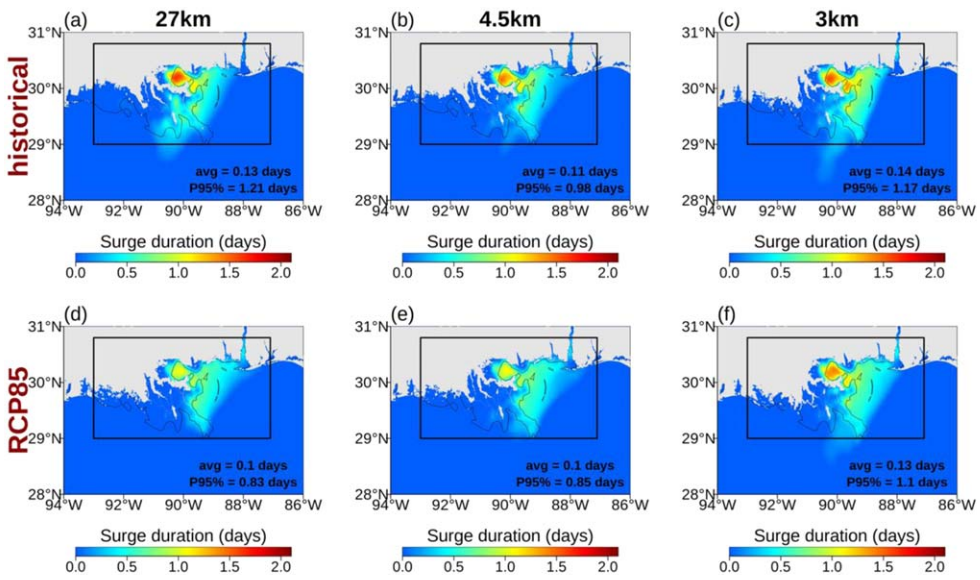

Figure 4. (a)–(f) Ensemble mean storm surge duration (days) for the (a)–(c) historical and (d)–(f) future surge simulations for the 27 km, 4.5 km and 3 km meteorological forcings. Surge duration is further computed within the subregion denoted by the black rectangle. The maps are slightly zoomed in (compared to figure 1) to better highlight areas with substantial surge duration.

region, most of which is offshore and has zero surge duration values, we further compared the 95th percentiles. The 95th percentiles are 1.21, 0.98, and 1.17 days respectively. The differences in surge duration across the three forcings may be a combination of TC track and size, landfall location, and the geophysical characteristics of the affected area as shown in previous studies (e.g., Akbar *et al* (2017) and Needham and Keim (2014)), although we did not investigate these in the current study.

In the future period, there is a marked difference in surge duration, with the highest values for the 3 km forcing. It should also be noted that there is a reduction in the storm surge duration from the historical to future periods across all three forcings (figures 4(d)–(f)), although less obvious for the 3 km resolution. The 95th percentile (average) of the surge duration across all ensembles within the subregion denoted by the black rectangle is 0.83 (0.1), 0.85 (0.1), and 1.1 (0.13) days for the 27, 4.5, and 3 km resolution forcings, respectively. These results demonstrate that the resolution of meteorological forcing can also influence both the duration of simulated storm surge and its future changes.

Given the increase in S_{peak} from the historical to future period, the decrease in the surge duration may appear somewhat counterintuitive. To understand this, we investigated the translation speed of the TC over the entire domain shown in figure 3. In the historical period, we found that the TC translation speed is slowest in the 3 km and fastest in the 27 km (figure 5(a)). This may be due to the different representations of dynamic processes influencing TC activity at various resolutions, although no studies currently provide evidence of hurricane translation speed dependence on horizontal resolution. For all horizontal resolution forcings, the translation speed increases in the future warmer climate. The mean TC translation speed increases by 5%, 5.5%, and 8.7% in the 27, 4.5, and 3 km resolution forcings, respectively. The increase in translation speed contrasts with recent trend studies that have shown that global TC translation speeds have slowed down in response to global warming (Kossin 2018), although we only consider one TC event here, while the trend study analysis was based on multiple events, therefore, our result is not generalizable. Additionally, we only considered the part of Hurricane Katrina's track that passes through the domain shown in figure 4.

We further investigated the lifetime of the TC over the ocean since it is the TC winds over the ocean that force water from the deeper ocean to cause surges near the coast. Figure 5(b) shows the percentage of TC lifetime on the ocean in the historical and future periods over all ten ensembles for the three meteorological forcing resolutions. Across all three forcings, the ensemble mean percentage of TC ocean lifetime is reduced by ~5% from the historical to the future period. Moreover, it is important to note that the ensemble mean percentage of TC lifetime over the ocean is similar across all three forcings in either the historical or future periods (i.e., ~65% and 60% in the historical and future periods, respectively). This further helps to explain the decrease in surge duration from the historical to future periods.

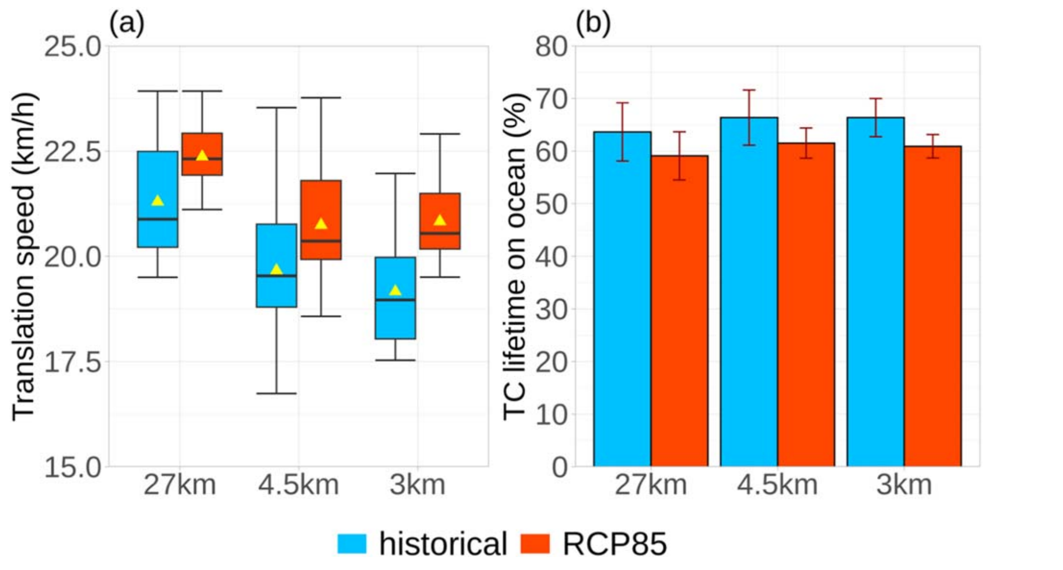

Figure 5. Comparison of (a) TC translation speed across all ensembles and (b) ensemble mean percentage of TC ocean lifetime between the historical and future periods for all three forcings. The yellow triangle represents the ensemble mean values. The error bars represent the ensemble spread.

4. Discussion and conclusions

This study investigated whether and how the storm surge caused by Hurricane Katrina could change if a similar event occured in a future warmer climate. Additionally, we investigated how these potential changes vary when using atmospheric forcings of different resolutions. We used regional climate model simulations of Hurricane Katrina at 27, 4.5, and 3 km resolutions to drive storm surge simulations with the ADCIRC model in the historical period and a hypothetical future warmer climate. For all the resolutions, we found statistically significant increases in the peak surge height in the future. With a 3 km resolution meteorological forcing, which corresponds to a typical RCM horizontal resolution, the 95th percentile of peak surge height (S_{peak}) over the area of highest surge increases from 5.4 m in the historical to 6 m in the future climate. At 27 km, which currently corresponds to the typical highest resolution of GCMs (e.g., the HighResMIP), the 95th percentile of S_{peak} increases from 4.4 m in the historical to 4.8 m in the future climate. The magnitude of S_{peak} increase is 22% greater in the 3 km forcing compared to the 27 km forcing. This is considerable given that the difference in peak surge height between the 3 km and 27 km was statistically significant in both climates.

The simulated S_{peak} in the future could even be higher when the impact of sea level rise (SLR) is considered, although this was not considered in the present study. Based on an ensemble of models and warming scenarios, the global SLR is projected to be in the range of 0.25 to 2 m by the end of the century (Rahmstorf 2010, Hall *et al* 2016, Sweet *et al* 2017, Oppenheimer *et al* 2022), although SLR itself and its impact on storm surge is not regionally constant. For instance, as shown by previous studies (e.g., Smith *et al* 2010, Bilskie *et al* 2014, Irish *et al* 2014), many areas with shallow water, fringing marshes, or irregular shoreline geometries are likely to experience storm surge increases that are almost double the effects of SLR by itself, whereas locations in the deeper ocean or open coastline will experience only small nonlinear effects of SLR.

Our results also showed differences between the resolutions for the spatial extent of the changes in peak storm surge. The change in the simulated peak surge height between the historical and future periods is considerably more spatially extensive under the 27 km forcing. This was primarily linked to an increase in the TC size within the 27 km forcing. We also found that the 95th percentile of surge duration decreases from 1.2 days in the historical to 1.1 days in the future climate when using the 3 km forcing. Similarly, it decreases from 1.2 to 0.8 days from the historical to the future period when using the 27 km forcing. We linked this to increasing TC translation speed, as well as a decrease in time the TC spends over the ocean in the future. While the surge duration decreased across all the forcings, the magnitude was sensitive to the resolution, decreasing by 31% at 27 km to 6 % at 3 km.

The increase in peak surge heights aligns with the findings of Irish *et al* (2014), which demonstrated that the flooding caused by the actual Katrina event was significantly greater than it would have been if it had occurred under the climatic conditions of 1900. Our results, therefore, indicate that a similar Katrina event in future could be even more devastating. However, it is important to note that this may not be the case for all tropical cyclone (TC) events, as demonstrated by Camelo *et al* (2020), who found that some TC events could result in negative changes in flooding volume under future warmer conditions. This discrepancy could potentially be attributed to shifts in TC tracks under future climates as shown in their work. Even slight track alterations could lead to landfall in areas with significantly different coastline geometries. A way to investigate the potential changes while eliminating the influence of track shifts could be forcing the surge model with best track data, while perturbing the intensity to mimic those in warmer climates. In our case, shifts in TC tracks could be further complicated by the different horizontal resolutions, and highlights the need for further investigation.

While our work shows that Hurricane Katrina's surge will increase in the future regardless of the atmospheric forcing resolution, there are some limitations that should be considered in future studies. First, our results on future increasing S_{peak} and decreasing surge durations cannot be generalized, as our simulations are based on a single TC event. Moreover, the future climate perturbations for the TC event are estimated from a single climate model (i.e., CCSM4) and the RCP8.5 scenario. Thus, using other climate models and scenarios may lead to different changes. Similarly, different climate models have different physics configurations and may not necessarily produce similar surges as those in the WRF model simulations used for this study. Therefore, it may be necessary to explore future surge changes based on different climate models and future scenarios in future studies. Nevertheless, we have shown that simulated storm surge is sensitive to the horizontal resolution of the driving meteorological forcing, whether in the historical or future period. While TC-permitting resolution forcings can project the sign of future changes in peak surge height and surge duration, our results show that there are significant differences in the magnitude of projections when compared with convection-permitting resolutions. Thus, convection-permitting resolution forcings are preferred, especially for future storm surge projections, as TC-permitting resolutions may not be sufficient to capture the magnitude of peak surge height projections.

Acknowledgments

This material is based upon work supported by the US Department of Energy, Office of Science, Office of Biological and Environmental Research (BER), Earth and Environmental Systems Modeling (EESM) Program, under Early Career Research Program Award Number DE-SC0021109. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a US Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC02–05CH11231 using NERSC award BER-ERCAP-m1517. The authors would like to thank Casey Dietrich for his comments during the analyses. We thank Rick Luettich and the ADCIRC Development Group for developing the ADCIRC model (https://adcirc.org/) and Crystal Fulcher for providing access to the ADCIRC code. We thank three anonymous reviewers for their constructive comments that have helped improve the manuscript.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10459386.

Open research

The WRF simulations data are available at https://portal.nersc.gov/cascade/TC. The WRF model code is available at https://www2.mmm.ucar.edu/wrf/users/download/get_sources.html. The NOAA water elevation observations are available at https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels.

ORCID iDs

Derrick K Danso https://orcid.org/0000-0001-7141-7530
Christina M Patricola https://orcid.org/0000-0002-3387-0307

References

Akbar M, Kanjanda S and Musinguzi A 2017 Effect of bottom friction, wind drag coefficient, and meteorological forcing in hindcast of hurricane rita storm surge using SWAN + ADCIRC Model *Journal of Marine Science and Engineering* **5** 38

Ayyad M, Hajj M R and Marsooli R 2023 Climate change impact on hurricane storm surge hazards in New York/New Jersey coastlines using machine-learning *Npj Climate and Atmospheric Science* **6** 88

Bacmeister J T, Reed K A, Hannay C, Lawrence P, Bates S, Truesdale J E, Rosenbloom N and Levy M 2018 Projected changes in tropical cyclone activity under future warming scenarios using a high-resolution climate model *Clim. Change* **146** 547–60

Bhatia K, Vecchi G, Murakami H, Underwood S and Kossin J 2018 Projected response of tropical cyclone intensity and intensification in a global climate model *J. Clim.* **31** 8281–303

Bilskie M V, Hagen S C, Medeiros S C and Passeri D L 2014 Dynamics of sea level rise and coastal flooding on a changing landscape *Geophys. Res. Lett.* **41** 927–34

Bloemendaal N, Muis S, Haarsma R J, Verlaan M, Irazoqui Apecechea M, de Moel H, Ward P J and Aerts J C J H 2019 Global modeling of tropical cyclone storm surges using high-resolution forecasts *Clim. Dyn.* **52** 5031–44

Butler T, Altaf M U, Dawson C, Hoteit I, Luo X and Mayo T 2012 Data assimilation within the advanced circulation (ADCIRC) modeling framework for hurricane storm surge forecasting *Mon. Weather Rev.* **140** 2215–31

Camelo J, Mayo T L and Gutmann E D 2020 Projected climate change impacts on hurricane storm surge inundation in the coastal United States *Frontiers in Built Environment* **6** 588049

Cardone V J and Cox A T 2009 Tropical cyclone wind field forcing for surge models: critical issues and sensitivities *Nat. Hazards* **51** 29–47

Colle B A, Buonaiuto F, Bowman M J, Wilson R E, Flood R, Hunter R, Mintz A and Hill D 2008 New York City's vulnerability to coastal flooding *Bull. Am. Meteorol. Soc.* **89** 829–42

Davis C, Wang W, Dudhia J and Torn R 2010 Does increased horizontal resolution improve hurricane wind forecasts *Weather and Forecasting* **25** 1826–41

Davis C A 2018 Resolving tropical cyclone intensity in models *Geophys. Res. Lett.* **45** 2082–7

Deb M and Ferreira C M 2018 Simulation of cyclone-induced storm surges in the low-lying delta of Bangladesh using coupled hydrodynamic and wave model (SWAN + ADCIRC) *J. Flood Risk Manage.* **11** S750–S765

Dietrich J C *et al* 2010 A high-resolution coupled riverine flow, tide, wind, wind wave, and storm surge model for southern louisiana and mississippi. II: synoptic description and analysis of hurricanes Katrina and Rita *Mon. Weather Rev.* **138** 378–404

Dietrich J C, Tanaka S, Westerink J J, Dawson C N, Luettich R A, Zijlema M, Holthuijsen L H, Smith J M, Westerink L G and Westerink H J 2012 Performance of the unstructured-mesh, SWAN+ADCIRC model in computing hurricane waves and surge *J. Sci. Comput.* **52** 468–97

Dube S K, Jain I, Rao A D and Murty T S 2009 Storm surge modelling for the Bay of Bengal and Arabian Sea *Nat. Hazards* **51** 3–27

Egbert G D and Erofeeva S Y 2002 Efficient inverse modeling of barotropic ocean tides *Journal of Atmospheric and Oceanic Technology* **19** 183–204

Fleming J G, Fulcher C W, Luettich R A, Estrade B D, Allen G D and Winer H S 2008 A real time storm surge forecasting system using ADCIRC *Estuarine and Coastal Modeling* **2007** 893–912

Fossell K R, Ahijevych D, Morss R E, Snyder C and Davis C 2017 The practical predictability of storm tide from tropical cyclones in the Gulf of Mexico *Mon. Weather Rev.* **145** 5103–21

Fu D, Chang P, Patricola C M, Saravanan R, Liu X and Beck H E 2021 Central American mountains inhibit eastern North Pacific seasonal tropical cyclone activity *Nat. Commun.* **12** 4422

Haarsma R J *et al* 2016 High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6 *Geoscientific Model Development* **9** 4185–208

Hall J, Gill S, Obeysekera J, Sweet W, Knuuti K and Marburger J 2016 *Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide.* U.S. Department of Defense, Strategic Environmental Research and Development Program p 224

Irish J L, Sleath A, Cialone M A, Knutson T R and Jensen R E 2014 Simulations of Hurricane Katrina (2005) under sea level and climate conditions for 1900 *Clim. Change* **122** 635–49

Jin H, Peng M S, Jin Y and Doyle J D 2014 An evaluation of the impact of horizontal resolution on tropical cyclone predictions using COAMPS-TC *Weather and Forecasting* **29** 252–70

Kates R W, Colten C E, Laska S and Leatherman S P 2006 Reconstruction of New Orleans after Hurricane Katrina: a research perspective *Proc. Natl Acad. Sci.* **103** 14653–60

Knabb R D, Rhome J R and Brown D P 2005 *Tropical Cyclone Report: Hurricane Katrina* National Hurricane Center *23–30 August, 2005*

Knutson T R *et al* 2020 Tropical cyclones and climate change assessment II: projected response to anthropogenic warming *Bull. Am. Meteorol. Soc.* **101** E303–22

Knutson T R, McBride J L, Chan J, Emanuel K, Holland G, Landsea C, Held I, Kossin J P, Srivastava A K and Sugi M 2010 Tropical cyclones and climate change *Nat. Geosci.* **3** 157–63

Kossin J P 2018 A global slowdown of tropical-cyclone translation speed *Nature* **558** 104–7

Kowaleski A M, Morss R E, Ahijevych D and Fossell K R 2020 Using a WRF-ADCIRC ensemble and track clustering to investigate storm surge hazards and inundation scenarios associated with hurricane irma *Weather and Forecasting* **35** 1289–315

Li H, Hu A and Meehl G A 2023 Role of tropical cyclones in determining ENSO characteristics *Geophys. Res. Lett.* **50** e2022GL101814

Lin N, Emanuel K, Oppenheimer M and Vanmarcke E 2012 Physically based assessment of hurricane surge threat under climate change *Nat. Clim. Change* **2** 462–7

Luettich R A, Westerink J J and Scheffner N W 1992 *ADCIRC: An Advanced Three Dimensional Circulation Model for Shelves, Coasts and Estuaries. Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL.* DRP-92-6 Rept.1 Department of the Army, US Army Corps of Engineers

Marsooli R, Lin N, Emanuel K and Feng K 2019 Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns *Nat. Commun.* **10** 3785

Mayo T, Butler T, Dawson C and Hoteit I 2014 Data assimilation within the Advanced Circulation (ADCIRC) modeling framework for the estimation of Manning's friction coefficient *Ocean Modell.* **76** 43–58

Mori N, Shimura T, Yoshida K, Mizuta R, Okada Y, Fujita M, Khujanazarov T and Nakakita E 2019 Future changes in extreme storm surges based on mega-ensemble projection using 60-km resolution atmospheric global circulation model *Coastal Engineering Journal* **61** 295–307

Needham H F and Keim B D 2014 An empirical analysis on the relationship between tropical cyclone size and storm surge heights along the U.S. Gulf Coast *Earth Interact.* **18** 1–15

Oppenheimer M *et al* 2022 *Sea level Rise and Implications for Low-Lying Islands, Coasts and Communities. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* Intergovernmental Panel on Climate Change. Cambridge University Press 321–446

Pandey S and Rao A D 2019 Impact of approach angle of an impinging cyclone on generation of storm surges and its interaction with tides and wind waves *Journal of Geophysical Research: Oceans* **124** 7643–60

Patricola C M, Saravanan R and Chang P 2017 A teleconnection between Atlantic sea surface temperature and eastern and central North Pacific tropical cyclones *Geophys. Res. Lett.* **44** 1167–74
Patricola C M and Wehner M F 2018 Anthropogenic influences on major tropical cyclone events *Nature* **563** 339–46
Rahmstorf S 2010 A new view on sea level rise *Nat. Clim. Change* **1** 44–5
Rappaport E N 2014 Fatalities in the United States from Atlantic tropical cyclones: new data and interpretation *Bull. Am. Meteorol. Soc.* **95** 341–6
Rego J L and Li C 2010 Nonlinear terms in storm surge predictions: effect of tide and shelf geometry with case study from Hurricane Rita *Journal of Geophysical Research: Oceans* **115** C06020
Riverside Technology and AECOM 2015 *Mesh Development, Tidal Validation, and Hindcast Skill Assessment of an ADCIRC Model for the Hurricane Storm Surge Operational Forecast System on the US Gulf-Atlantic Coast.* (https://doi.org/10.17615/4z19-y130)
Roberts M J *et al* 2020 Impact of model resolution on tropical cyclone simulation using the HighResMIP–PRIMAVERA multimodel ensemble *J. Clim.* **33** 2557–83
Saha S *et al* 2010 The NCEP climate forecast system reanalysis *Bull. Am. Meteorol. Soc.* **91** 1015–58
Salarieh B, Ugwu I A and Salman A M 2023 Impact of changes in sea surface temperature due to climate change on hurricane wind and storm surge hazards across US Atlantic and Gulf coast regions *SN Applied Sciences* **5** 205
Schär C, Frei C, Lüthi D and Davies H C 1996 Surrogate climate-change scenarios for regional climate models *Geophys. Res. Lett.* **23** 669–72
Sebastian A, Proft J, Dietrich J C, Du W, Bedient P B and Dawson C N 2014 Characterizing hurricane storm surge behavior in Galveston Bay using the SWAN+ADCIRC model *Coastal Eng.* **88** 171–81
Shimura T, Pringle W J, Mori N, Miyashita T and Yoshida K 2022 Seamless projections of global storm surge and Ocean waves under a warming climate *Geophys. Res. Lett.* **49** e2021GL097427
Smith J M, Cialone M A, Wamsley T V and McAlpin T O 2010 Potential impact of sea level rise on coastal surges in southeast Louisiana *Ocean Eng.* **37** 37–47
Sun Y, Yi L, Zhong Z, Hu Y and Ha Y 2013 Dependence of model convergence on horizontal resolution and convective parameterization in simulations of a tropical cyclone at gray-zone resolutions *Journal of Geophysical Research: Atmospheres* **118** 7715–32
Sweet W V, Kopp R E, Weaver C P, Obeysekera J, Horton R M, Thieler R E and Zervas C 2017 *Global and Regional Sea Level Rise Scenarios for the United States.* NOS CO-OPS 083 National Oceanic and Atmospheric Administration (https://doi.org/10.7289/V5/TR-NOS-COOPS-083)
Thomas A, Dietrich J, Asher T, Bell M, Blanton B, Copeland J, Cox A, Dawson C, Fleming J and Luettich R 2019 Influence of storm timing and forward speed on tides and storm surge during Hurricane Matthew *Ocean Modell.* **137** 1–19
Weaver R J and Slinn D N 2010 Influence of bathymetric fluctuations on coastal storm surge *Coastal Eng.* **57** 62–70
Westerink J J, Luettich R A, Feyen J C, Atkinson J H, Dawson C, Roberts H J, Powell M D, Dunion J P, Kubatko E J and Pourtaheri H 2008 A basin- to channel-scale unstructured grid hurricane storm surge model applied to Southern Louisiana *Mon. Weather Rev.* **136** 833–64
Zhang C and Li C 2019 Effects of hurricane forward speed and approach angle on storm surges: an idealized numerical experiment *Acta Oceanologica Sinica* **38** 48–56
Zhong L, Li M and Zhang D-L 2010 How do uncertainties in hurricane model forecasts affect storm surge predictions in a semi-enclosed bay? *Estuarine Coastal Shelf Sci.* **90** 61–72