Coastal Engineering 57 (2010) 62–70

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Influence of bathymetric fluctuations on coastal storm surge

R.J. Weaver [a,*], D.N. Slinn [b]

[a] University of North Carolina at Chapel Hill, Institute of Marine Sciences, Morehead City, NC 28557, USA
[b] University of Florida, Department of Civil and Coastal Engineering, Gainesville, Florida 32611, USA

ARTICLE INFO

Article history:
Received 4 April 2008
Received in revised form 21 September 2009
Accepted 25 September 2009

Keywords:
Storm surge
Set-up
Bathymetry
Flooding
Modeling
SWAN
ADCIRC
Water level

ABSTRACT

Natural events constantly alter nearshore bathymetric properties. Hurricanes particularly affect bathymetry as they pass over a body of water. To compute an accurate forecast or recreate a hurricane's effects through hindcasting techniques, an operational bathymetry data set must be known in advance. However, obtaining and maintaining current and accurate bathymetric data can be costly and difficult to manage. In this paper we examine the extent to which variations in nearshore bathymetry affect the storm surge at the coast. A common question for wave and surge modeling is, “how good is the bathymetric data?” If we can allow for a range of fluctuations in the bathymetry without significantly adjusting the results of the surge predictions, we can potentially save months of field work and millions of dollars. A one-dimensional (1D) analytical solution for waves and water level is developed for initial testing. In the 1D case we find that as long as the amplitudes of the bathymetric fluctuations are less than 60% of the original depth, the surge at the coast is within ±10% of the surge generated on the initial bottom slope. If the fluctuation produces a hole, a deepening of the local bathymetry, within 80% of the local water depth, the coastal storm surge calculated is still within 10% of the unperturbed value computed for bottom slopes shallower than 1:20. In addition, we find there is an optimum distance offshore for each sloped profile that corresponds to a depth between 25 and 40 m, beyond which the effects of bathymetric fluctuations begin to decrease. A coupled 2D modeling system is implemented to test our hypothesis along a realistic coastline. After selecting three study sites, we vary the bathymetry at the selected locations by ±20%. Consistent with the 1D tests, the storm surge at the shoreline varies by less than 5%.

1. Introduction

The increase in the mean sea level at the coast, in response to a disturbance such as a hurricane, is dependent on the bathymetric properties that lie hidden under the body of water bordering the coast. The depth and width of the continental shelf, as well as the average nearshore profile are important parameters for calculating wind set-up and wave set-up. The nearshore coastal bathymetry is important in calculating the formation and evolution of the waves generated by the winds. Thus, this nearshore region is important when calculating the forces created by the momentum flux as the waves shoal and break.

Unfortunately, obtaining and maintaining current and accurate bathymetric data can be costly and difficult to manage. At any given location, the bathymetric data available and the actual bathymetry will not agree 100%. When modeling storm surge, we rely on a spatially large data set that may have gaps in portions of the bathymetric data. It is also possible that the data provided may be outdated, or simply erroneous.

Current LiDAR technologies enable the scientist to map the sea floor up to the 20–60 m depth contour depending on the clarity of the water and wavelength of the laser, (Irish and Lillycrop, 1999; Irish and White, 1998; Danson, 2006). Typically, the LiDAR system is effective for depths of approximately 50 m, for very clear waters, to as shallow as less than 10 m, if a reliable signal can be received, for murky turbid waters. The general rule of thumb is, that LiDAR is effective to depth between 2 to 3 times the Secci depth (Guenther, 2004). The newer technologies are more cost effective for mapping the nearshore coastal bathymetry than using sonar. The estimated cost per square kilometer for a LiDAR survey is between $400 to more than $1500 depending on the size of the project, location and density of data required.

The bathymetric contours are in a constant state of change, as sediment is continuously transported both into, out of, and along the littoral zones. During storms, significant amounts of sediment can be displaced. These amounts of sediment can be transported offshore, as the coast erodes to a storm profile. The wind and wave generated currents transport the mobilized sediment both offshore

* Corresponding author. UNC CH Inst. of Marine Sciences, 3431 Arendell St., Morehead City, NC 28557, USA. Tel.: +1 252 726 6841x124.
E-mail addresses: weav999@yahoo.com, rjweaver@email.unc.edu (R.J. Weaver).

0378-3839/$ – see front matter
doi:10.1016/j.coastaleng.2009.09.012

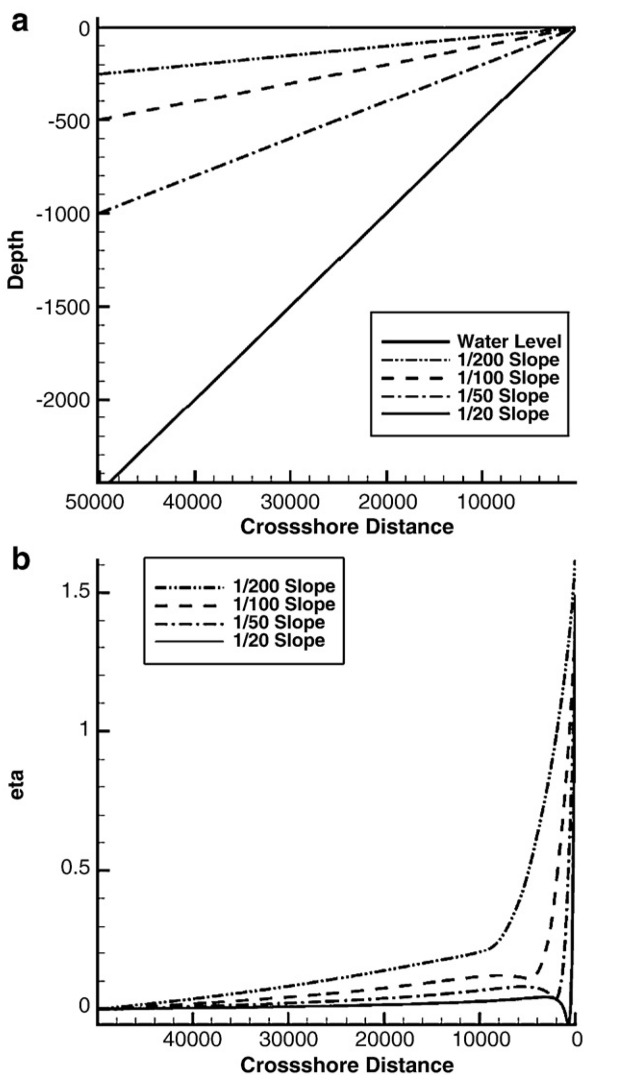

Fig. 1. 1D bathymetric profiles and corresponding storm surge. Units for distance, depth and surge are meters. a) A composite plot of the 4 bathymetric profiles (1:20, 1:50, 1:100, and 1:200). b) Corresponding surge plotted for each of the 4 profiles (forcing for storm surge calculation includes wind and wave data).

and alongshore. During the lower energy events this sediment is slowly moved back onshore. Overwash is another process by which sediment is moved. These examples illustrate the complexity of sediment transport, and the fact that bathymetry changes can take place over very short timescales as well as longer timescales.

In this paper we examine the extent to which variations in nearshore bathymetry affect the storm surge at the coast. If we can allow for a range of fluctuations in the local bathymetry without adversely affecting the results of the surge predictions, we can potentially save months of field work and millions of dollars.

In order to answer this question, we create a 1D idealized bathymetry. This bathymetry is altered by adding a local Gaussian disturbance at various distances from the shoreline. We are defining the perturbation as a percentage of the local water depth. Our perturbations are scaled by depth; therefore, for a given percentage difference, these perturbations will be smaller in shallower waters and larger in deeper waters. A wind is blown across the domain and a wave field is calculated. From this we generate a surge profile across the domain. By altering the size and location of this disturbance and recording the effect on the surge level at the coast, we gain insight to the effects a 3D disturbance might have. Maa et al. (2004) found, in a study of offshore sand mining, that the effects on storm surge at the coast were negligible. We seek to expand on this work, and cover a wide range of altered profiles, perturbing both up and down.

To more accurately simulate real conditions we use a two-dimensional coupled modeling system developed by Weaver and Slinn (Weaver, 2008; Niedoroda et al., 2007). This coupled 2D modeling system is implemented to test our hypothesis along a realistic coastline, the Gulf Coast from Florida to Louisiana. The wave model SWAN and the circulation model, ADCIRC, are coupled through a series of scripts and pre-/post-processing programs. Given an input bathymetry domain, or a series of domains for nesting, and an input meteorological forcing, the system will process the wave and surge predictions from an initial prediction to a final result.

2. Methodology

2.1. Introduction

Both 1D and 2D tests are performed in order to gain a more complete understanding of the processes. We couple basic analytical knowledge of storm surge and wave set-up with a 3rd generation wave model for our 1D tests. The 1-D tests are performed using a constant wind forcing. The second set of tests uses 2D modeling programs coupled together. Additionally, the 2-D tests are forced using post-analysis winds for hurricanes Ivan and Katrina, a hybrid bottom friction formula and horizontal diffusion terms. Both systems are briefly described below.

2.2. 1D tests

In order to test the sensitivity of surge to the quality of bathymetric data, we first employ a 1D modeling system. This quasi-analytic model provides a solution for the surge at the coast using Eq. (1). This equation is a modified version of equations given in Dean and Dalrymple (1991, 2002), where we have added the wave forcing term. The 1.25 multiplier is a factor that lumps the effect of bottom shear stress and wind shear stress and is greater than 1.0, with accepted values between 1.15 and 1.3, (U.S Army, C. E. R. C., 1977). The wave forcing component is calculated using the SWAN wave model (Holthuijsen, 2000).

$$\frac{\partial \eta}{\partial x} = \frac{1}{\rho g(h+\eta)}\left[-\frac{\partial S_{xx}}{\partial x} + 1.25\tau_{xx}\right] \quad (1)$$

Four bathymetric domains are created. Each is a simple sloping bottom. The values for the changes in depth are 1:20, 1:50, 1:100, and 1:200. These slopes represent a range of average nearshore profiles, which we then extend out to 50 km offshore. Fig. 1 shows the unperturbed bathymetries. To have a baseline data set, we generate surge predictions on the sloped profiles. Fig. 1 shows the associated surge for each of the four sloping bathymetries. These surge levels will be the baseline values to which we will later compare our results.

For each of these cases a suite of Gaussian disturbances are created. The disturbances are defined by their amplitudes, their widths, and the distance offshore of the peak of the curve. The amplitude, A, is defined as a percent of the water depth at the chosen peak location, and ranges from $\pm 100\%$ of the local bathymetry, varying in 20% increments. The width is determined using five values, 100, 500, 1000, 2500, and 5000 m for the standard deviation, σ_{st}, in Eq. (2). The location of the center of the disturbance measured in distance offshore, x_o, increases in 500 m increments from 500 m up to 5 km. The final shape of the disturbance is calculated using these three parameters in Eq. (2).

$$disturbance = (1 + A)\exp\frac{-(x - x_0)^2}{(2\sigma_{st})^2} \qquad (2)$$

There are fifty profiles used at each of the ten locations offshore, so that five hundred profiles are used for each of the four initial sloped domains, for a total of two thousand realizations. For each bathymetric domain we simulate a 50 m/s wind blowing directly onshore, $U = 50$ m/s, $V = 0$. The wind stress, τ_{xx}, is calculated using Van Dorn's formula for wind stress, S_{vd}, taken from Dean and Dalrymple (1991) as expressed in Eq. (3).

$$\tau_{xx} = \rho S_{vd} U|U|$$

$$\text{where, } S_{vd} = 1.2E^{-6} + 2.25E^{-6}(1 - (W_c/|U|))^2$$

$$\text{and, } W_c = 5.6m/s \qquad (3)$$

The winds are then read into SWAN, and a 1D wave field is computed. The resulting forces are then used in the computation of the surge, Eq. (1) along the bathymetric crossshore domain.

Representative plots of the suite of perturbed domains from the 1:100 initial slope, and the corresponding surge profile for each bathymetric profile, are shown in Fig. 2 for offshore distances of 500 m, 1000 m, 2000 m and 4000 m. The figure has four plots differing in the crossshore location of the perturbation and therefore water depth at the that location in the absence of the disturbance.

- Fig. 2(a), located 500 m from the shoreline in 5 m of water.
- Fig. 2(b), located 1000 m from the shoreline in 10 m of water.
- Fig. 2(c), located 2000 m from the shoreline in 20 m of water.
- Fig. 2(d), located 4000 m from the shoreline in 40 m of water.

When the amplitude of the disturbance is positive, the profile is made shallower, there is a greater surge level predicted at the coast for each case. Additionally, when the perturbation is wide, having a large standard deviation, there is a greater surge response at the shoreline.

2.3. Two-dimensional tests

To more accurately simulate real conditions, we implement a two-dimensional coupled modeling system developed by Weaver and Slinn (Weaver, 2008; Niedoroda et al., 2007). The wave model SWAN and the Circulation model, ADCIRC (Luettich et al., 1992), are coupled through a series of scripts and pre-/post-processing programs. Post-analysis wind and pressure fields for hurricanes Ivan and Katrina developed by OceanWeather, Inc. are used as meteorological forcing. The system has been extensively tested and validated. The predictive performance of both models is increased by the two-way coupling that is achieved. Coastal waves are more accurately predicted by including the increase in water levels from the surge model (Weaver and Slinn, 2006). In turn, the surge is more accurately predicted by including the wave forcing data (Weaver, 2004). Given an input bathymetry domain, or a series of domains for nesting, and an input meteorological forcing, the system will process the wave and surge predictions from an initial prediction to a final result.

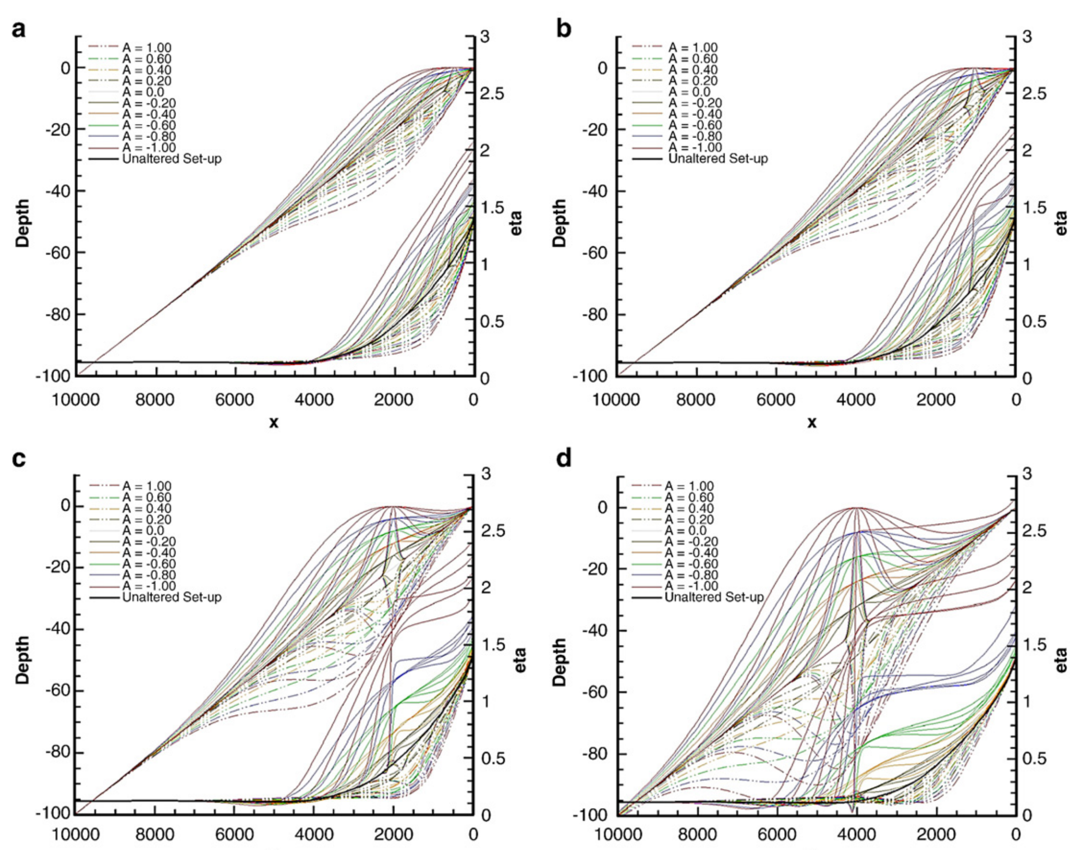

Fig. 2. Bathymetric displacements and surge profiles for initial slope 1:100. Center of displacement located at: a) 500 m in 5 m depth, b) 1000 m in 10 m depth, c) 2000 m in 20 m depth, and d) 4000 m in 40 m depth. Units for distance, depth and surge are meters.

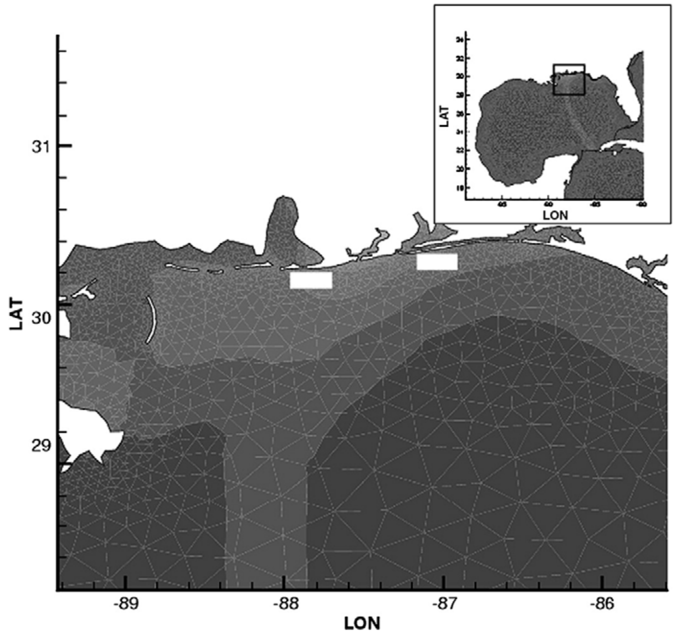

Fig. 3. The plot shows the locations of the ±20% Gaussian perturbations that were applied near the 15 m contour just east of the entrance to Mobile Bay and 25 m contour level just east of the entrance to Pensacola Bay. The inset box shows the location of the study area with respect to the Gulf of Mexico. The highlighted boxes indicate the locations of the test sites. X and Y axis units are in degrees Longitude and degrees Latitude respectively.

In order to test the sensitivity of the models to the bathymetry, we alter the bathymetric inputs. A two-dimensional Gaussian perturbation, Eq. (4), with amplitude of ±20% the base bathymetric depth at the center of the perturbation was applied to each of the chosen sites.

$$disturbance = (1+0.20)\exp-\left(\frac{(x-x_0)^2}{(2\sigma_{stx})^2}-\frac{(y-y_0)^2}{(2\sigma_{sty})^2}\right) \qquad (4)$$

For all of the perturbations we choose the alongshore width to be defined by $\sigma_{stx}=4000$ m and the crossshore width to be defined by $\sigma_{sty}=1500$ m. Where σ_{stx} and σ_{sty} are the standard deviations in the x and y directions respectively. This methodology is employed for three depths at four locations, and we use two historic hurricanes to force the locations. We test the sensitivity to bathymetric fluctuations close to the 15 m and 25 m contours using hurricane Ivan forcing, and close to the 5 m and 15 m contour using hurricane Katrina forcing. We chose the 5 m, 15 m and 25 m contours based on results from the 1D tests. Our 1D tests showed that varying the bathymetry deeper than the 30 m contour would not significantly alter the surge at the coast. More on this result is discussed below. The specific regions that we choose to alter were picked based on the profile and the relevant coastal contours mentioned above. The altered regions are within the influence of the storm chosen to force that domain.

We chose a coastal region just south of Pensacola Florida east of the inlet to Pensacola Bay, and then varied the bathymetry near the 25 m contour. The second location is just east of the entrance to Mobile Bay. At this location we vary the depth near the 15 m contour. These locations are shown in Fig. 3. In Fig. 4, we plot the altered bathymetric contours for both of the locations used with the Ivan forcing. Fig. 4(a) and (b) shows the area located just east of

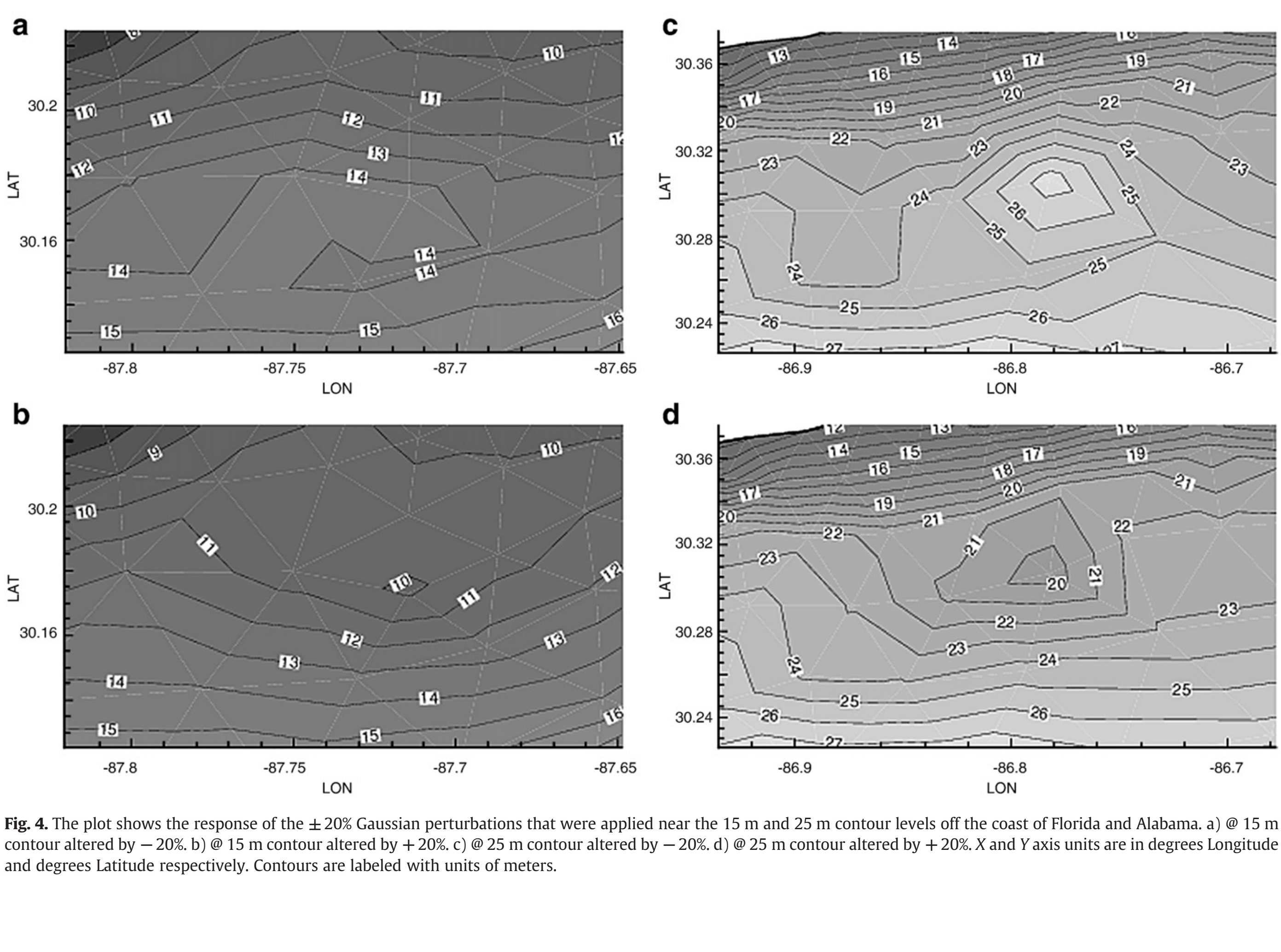

Fig. 4. The plot shows the response of the ±20% Gaussian perturbations that were applied near the 15 m and 25 m contour levels off the coast of Florida and Alabama. a) @ 15 m contour altered by −20%. b) @ 15 m contour altered by +20%. c) @ 25 m contour altered by −20%. d) @ 25 m contour altered by +20%. X and Y axis units are in degrees Longitude and degrees Latitude respectively. Contours are labeled with units of meters.

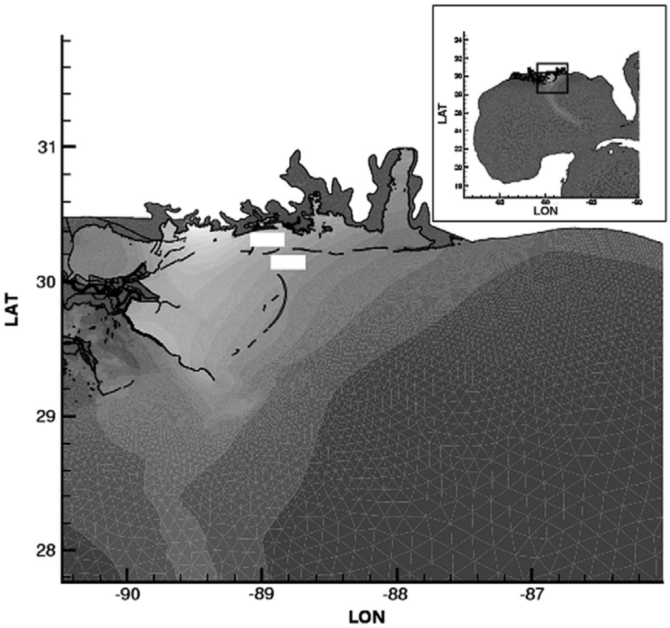

Fig. 5. The plot shows the locations of the ±20% Gaussian perturbations that were applied near the 5 m and 15 m contour levels off the coast of Mississippi. The inset box shows the location of the study area with respect to the Gulf of Mexico. The highlighted boxes indicate the locations of the test sites. The depth at the location closest to the shoreline varies from 3 to 5 m. The location further offshore just outside the barrier island is approximately 15 m deep. *X* and *Y* axis units are in degrees Longitude and degrees Latitude respectively.

Mobile Bay and Fig. 4(c) and (d) represents the area located just east of Pensacola Bay. For each of these four tests we use the Hurricane Ivan winds and pressures.

The locations of the sites where we perturbed the bottom and forced the surge with Hurricane Katrina winds and pressures are seen in Fig. 5. We chose a location in Mississippi Bay near the 5 m contour and one just outside the barrier island chain near the 15 m contour. In Fig. 6 we plot the altered bathymetric contours for both of the locations used with the Katrina forcing. Fig. 6(a) and (b) is located just offshore of Gulfport, MS inside Mississippi Sound at about 5 m depth. Fig. 6(c) and (d) is located just south of East Ship Island at about 15 m depth. The modified bathymetry is used for both the wave and circulation predictions.

The first step of the 2D computational process develops the deep water wave conditions and the initial nearshore wave predictions using SWAN, with no added water levels. The resultant wave forcing components are used in conjunction with the meteorological forcing data to run the ADCIRC model. This initial water level is very close to the actual water level, since the bulk of the surge is generated by the meteorological forcing components. These non-stationary water levels are then read in by the wave model SWAN at every time step. The new more accurate wave predictions will take into account the increased water levels, even flooded conditions. The final water level prediction is then computed with the coupled wave and meteorological data.

3. Results

3.1. 1-D results

Storm surge at the coast varies slightly as a consequence of local variation in the bathymetry. The plots from Fig. 2 show the raw results

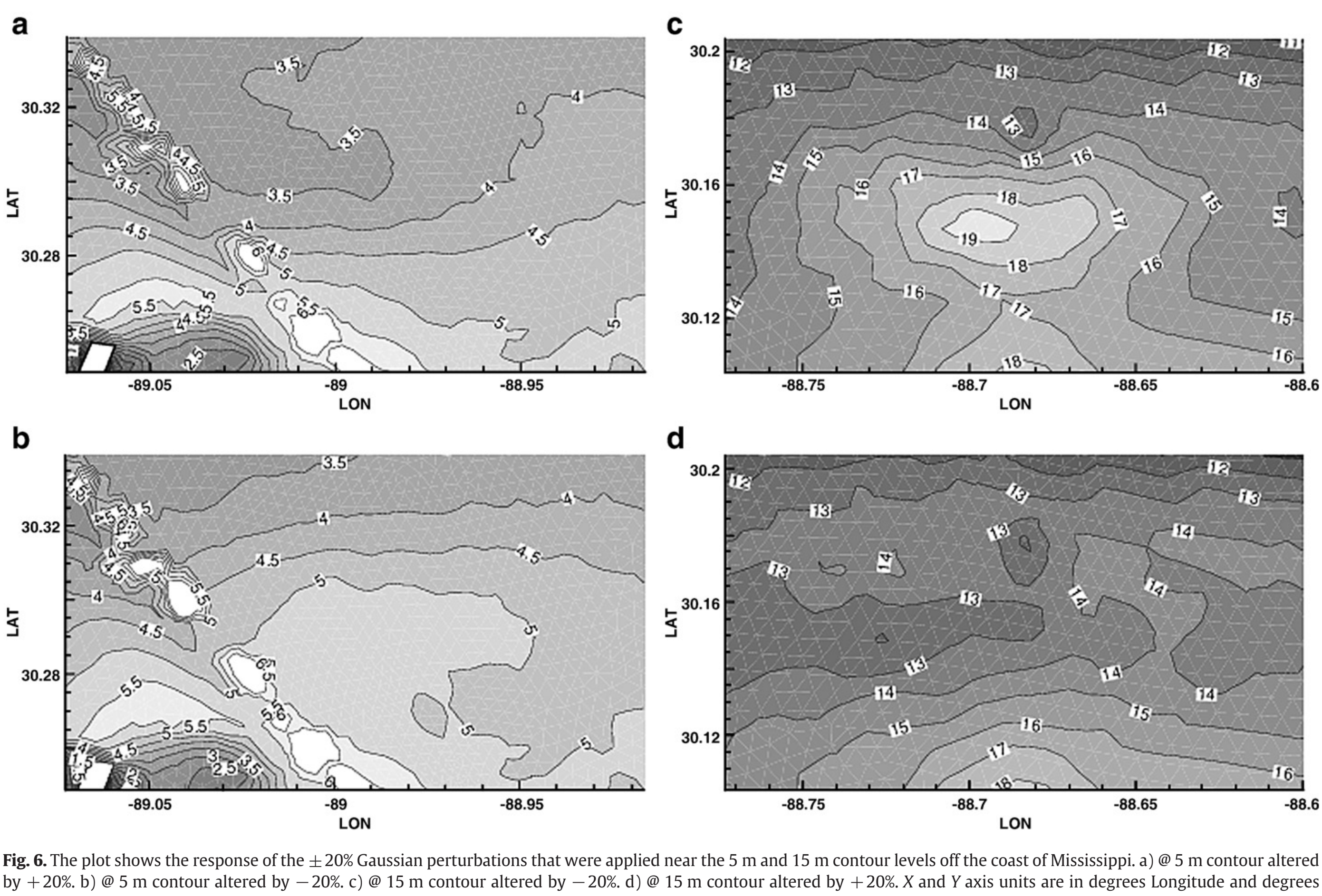

Fig. 6. The plot shows the response of the ±20% Gaussian perturbations that were applied near the 5 m and 15 m contour levels off the coast of Mississippi. a) @ 5 m contour altered by +20%. b) @ 5 m contour altered by −20%. c) @ 15 m contour altered by −20%. d) @ 15 m contour altered by +20%. *X* and *Y* axis units are in degrees Longitude and degrees Latitude respectively. Contours are labeled with units of meters.

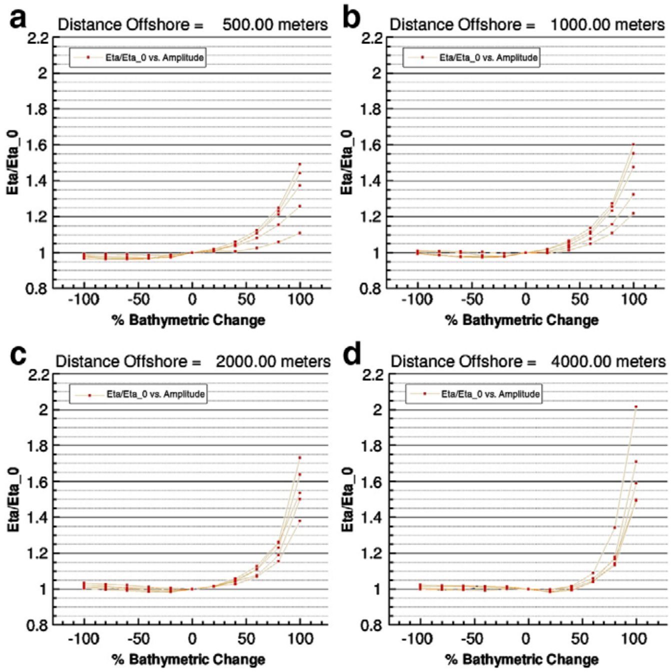

Fig. 7. $\frac{\eta}{\eta_0}$ vs amplitude on bottom slope 1:100. Center of displacement located at: a) 500 m in 5 m depth, b) 1000 m in 10 m depth, c) 2000 m in 20 m depth, and d) 4000 m in 40 m depth.

for selected cases. The bulk of the simulations predict the surge levels at the shore to be very close to that of the unperturbed sloping bottom. We divide each result by the result from the corresponding unaltered domain; a value of 1.0 corresponds to no difference between the cases.

We found that the resulting surge varied by ±10% for amplitude variations that were less than ±40% of the initial bathymetry. Fluctuations up to +60% would generate a difference at the coast of at most +20%.

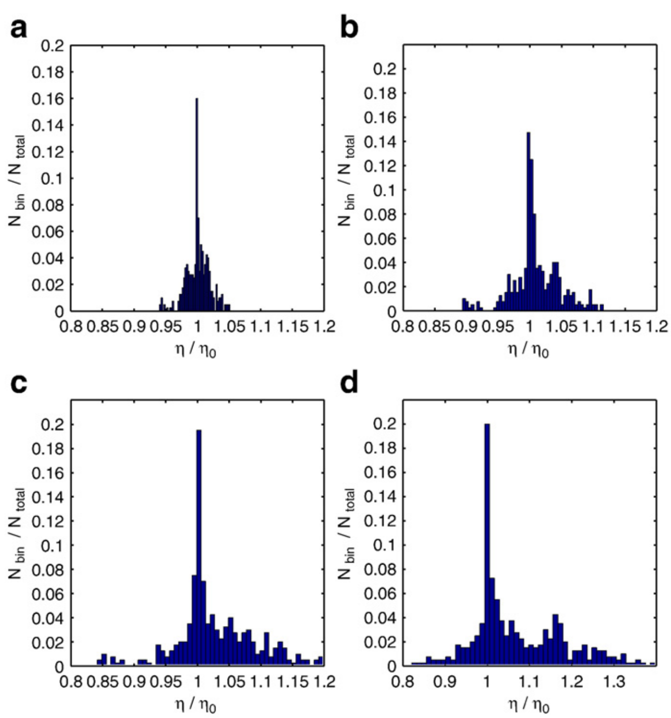

Fig. 8. Expected values of $\frac{\eta}{\eta_0}$ for given amplitudes. a) $A = \pm 20\%$ and corresponding RMSD = 1.87%, b) $A = \pm 40\%$ and corresponding RMSD = 3.86%, c) $A = \pm 60\%$ and corresponding RMSD = 6.79%, and d) $A = \pm 80\%$ and corresponding RMSD = 12.67%.

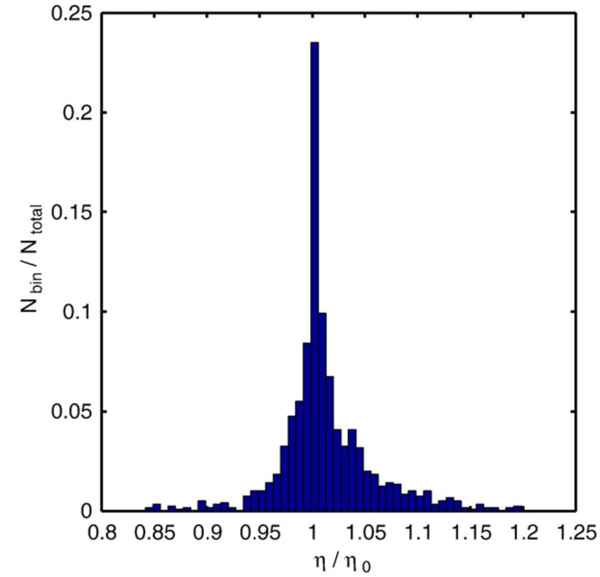

Fig. 9. Combined likelihood of $\frac{\eta}{\eta_0}$ for all 20, 40 and 60% perturbations. The combined data from the 20, 40 and 60% perturbations, plotted as a histogram. The RMSD for all 1200 cases shown here is 4.59%.

Fig. 7 shows the relative surge vs. amplitude of perturbation for the selected cases plotted in Fig. 2.

We also looked at the relative surge vs. the width of the perturbation. The wider disturbances generated a greater deviation from the unperturbed result. In the limit of an infinitely large σ_{st}, that is if we were to keep widening the disturbance, we would end up creating a new shallower, or deeper, profile.

As the center of the perturbation moves farther offshore, the relative depth increases depending on the average bottom slope. We find that there is a limit where, beyond this distance, the effects of bathymetric fluctuations at the shore begin to diminish. For all cases, this limit coincides with a depth of about 30 m. Seaward of that limit, the effects of altering the bathymetry begin to diminish. Beyond that

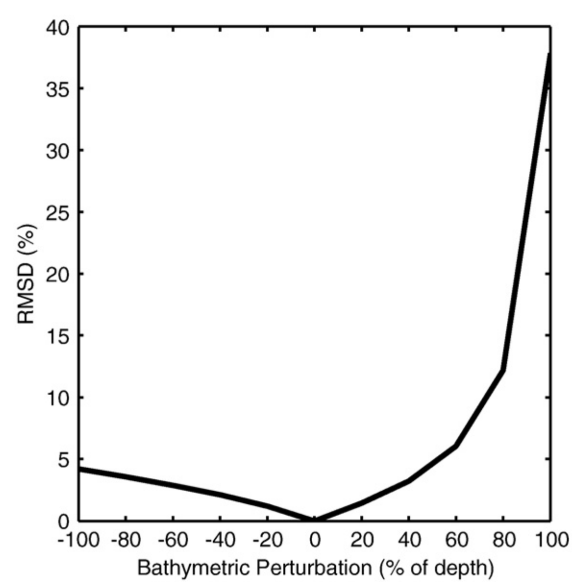

Fig. 10. RMSD vs. disturbance amplitude for all perturbations. RMSD between the calculated surge on the altered profiles and the surge calculated on the original sloping bottoms for all 2000 cases. The RMSD is plotted with respect to the amplitude of the bathymetric perturbation. For the perturbations that make the profile shallower the surge response is more pronounced than those that make the profile deeper.

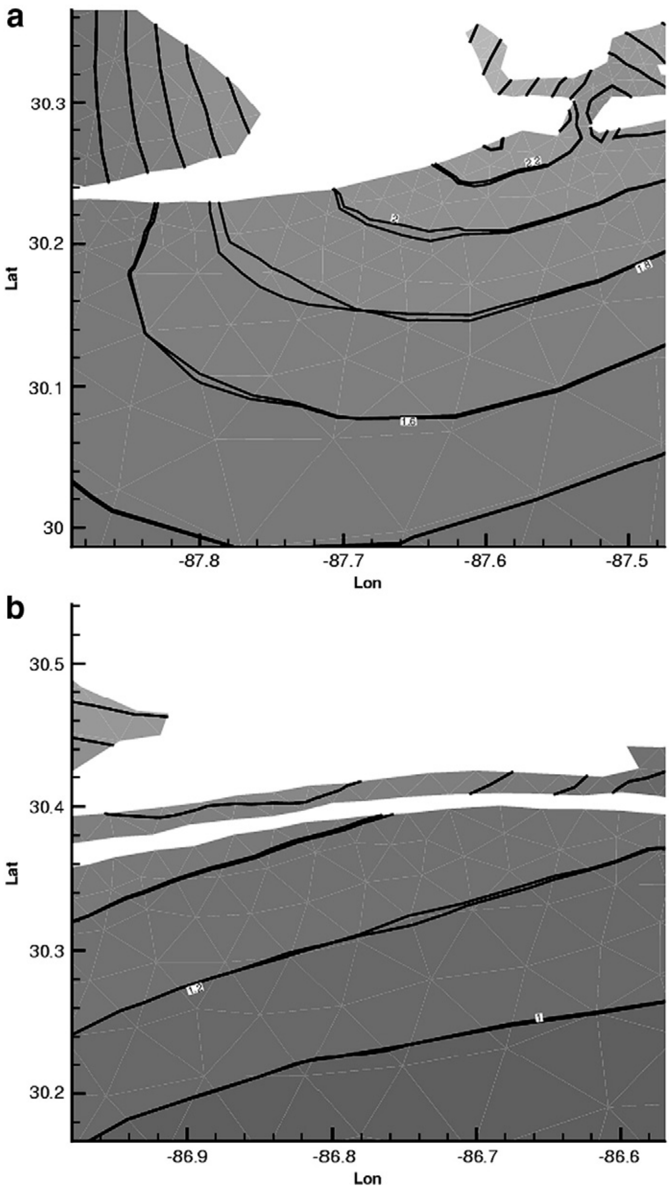

Fig. 11. Surge responses to altered bathymetries along the Alabama/Florida coast. a) Shows the comparison just east of the entrance to Mobile Bay and b) shows the comparison at just east of the entrance to Pensacola Bay. Both plots show the surge response of a +20% and −20% variation in the bathymetric contours to hurricane Ivan forcing. The boxes in each plot indicate the region where a 2D Gaussian perturbation was applied. Both the positive and negative perturbation results are contoured together. *X* and *Y* axis units are in degrees Longitude and degrees Latitude respectively. Contours are labeled with units of meters.

limit it would not be productive to invest in costly high definition bathymetry data collection.

Grouping all the results together for each of the amplitudes, we examine the likelihood of the relative surge values. Fig. 8 shows the likelihood for ±20%, ±40%, ±60%, ±80%. For ±20%, Fig. 8a, all cases are within 5% of the original surge value with an RMS difference of 1.87%. For ±40%, Fig. 8b, nearly all cases are within 10% of the original surge value with an RMS difference of 3.86%. For these amplitudes, even the extreme cases do not create significant differences between the surge value at the coast from the unaltered case and the perturbed cases. As the perturbations get larger, we see that the cases of extreme width and proximity to the shoreline start to produce outliers in the results. For ±60%, Fig. 8c, all cases are within 20% of the original surge value with an RMS difference of 6.79%. For ±80%, Fig. 8d, all cases are within 40% of the original surge value with an RMS difference of 12.69%. With an amplitude of ±80% the likelihood of greater differences starts to become significant.

Fig. 9 shows a composite plot of the ±20%, ±40%, and ±60% results. All results from these 1200 cases are within 20% of the unperturbed surge values for the respective plain sloped profiles. The RMSD for the combined data is 4.59%. Separating out the positive perturbations from the negative ones, the RMSD is plotted versus amplitude of profile change in Fig. 10. Depending on the maximum acceptable RMSD allowed, we can allow for a range of bathymetric variations without significantly changing the surge results at the shoreline.

3.2. 2-D results

We plot the MEOW (the Maximum Elevation of Water) that shows the spatial distribution of the storm surge, and compare the predictions by

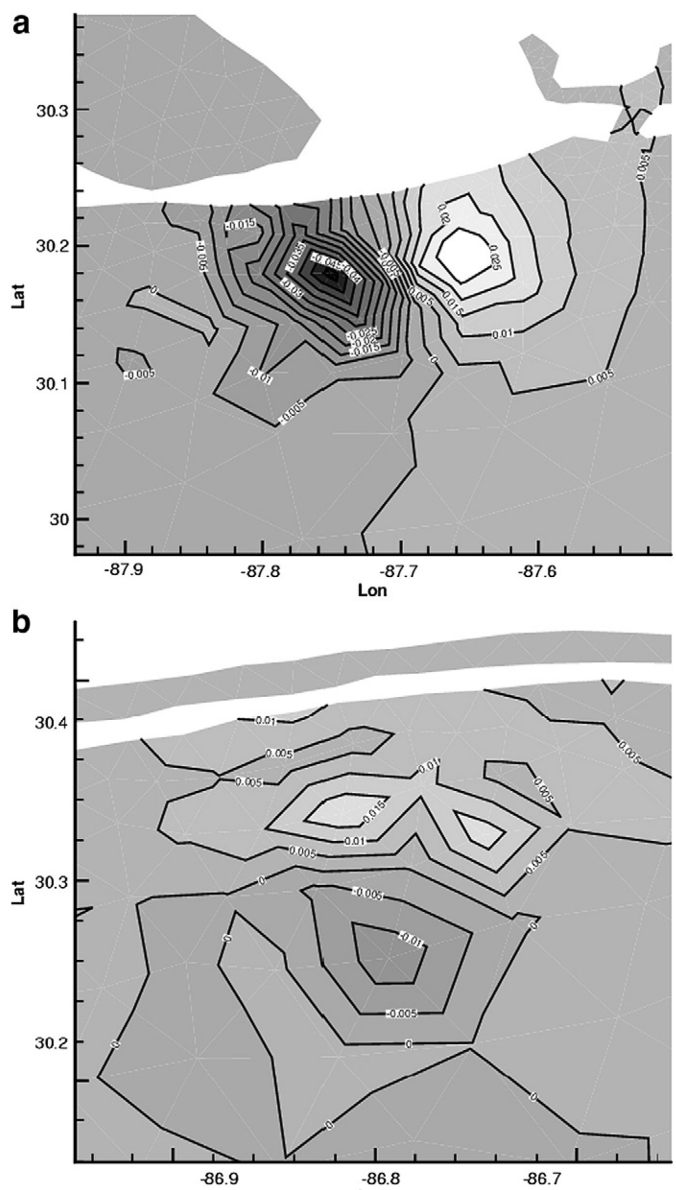

Fig. 12. Difference in surge responses to altered bathymetries at the 15 m and 25 m contour along the Alabama/Florida coast. a) Comparison at the 15 m contour level just east of the entrance to Mobile Bay. b) Comparison at the 25 m contour level just east of the entrance to Pensacola Bay. Both plots show the difference surge response of a +20% and −20% variation in the bathymetric contours to hurricane Ivan forcing. *X* and *Y* axis units are in degrees Longitude and degrees Latitude respectively. Contours are labeled with units of meters.

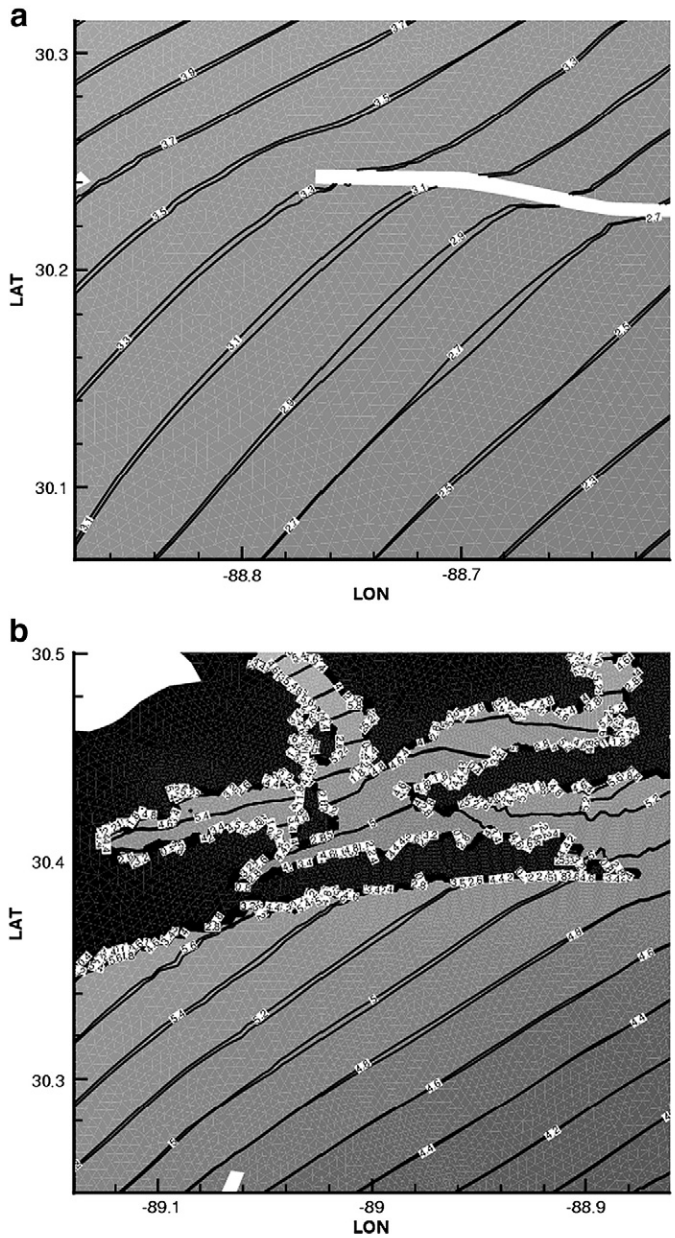

Fig. 13. Surge responses to altered bathymetries along the Mississippi coast. a) Comparison at the 15 m contour and b) Comparison at the 5 m contour. Both plots show the surge response of a +20% and −20% variation in the bathymetric contours to hurricane Katrina forcing. The boxes in each plot indicate the region where a 2D Gaussian perturbation was applied. Both the positive and negative perturbation results are contoured together. The two contour lines show window of results such perturbations would create. *X* and *Y* axis units are in degrees Longitude and degrees Latitude respectively. Contours are labeled with units of meters.

plotting the locations of the storm surge contour levels. The results from the 2D tests show that the surge at the coast does not vary more than +10% when we perturb the bottom by +20%, and the change is highly localized. We plotted the positive and negative perturbation results on top of each other in Figs. 11 and 13. The areas directly over the offshore bathymetry that were either perturbed to be deeper or shallower have slight observable shifts in the location of the contour lines. We see the greatest effect from perturbing near the 15 m contour. The lines realign with each other away from the perturbation and closer to the shoreline as seen in the 1D results.

Figs. 12 and 14 illustrate the differences between the results of the positive and negative perturbations at the four chosen site locations. We see a maximum difference of 2 cm where there is a surge level of about 2 m. This is consistent with the 10% differences we expect to see from the 1D study.

4. Conclusions

Near the coast, in waters less than 30 m, the importance of bathymetric fluctuation increases as the distance offshore decreases. Efforts to obtain accurate resolved bathymetric data should start at the shore and progress into deeper waters, as funding allows. Local knowledge of the study site is an important factor. Knowing how the bathymetry varies locally, can help focus resources for data gathering. As long as the local bathymetry fluctuation is within 60% of the water depth that would be computed for the average slope of the bottom at that location, the RMS difference in the surge at the coast will be within 4.59%. Furthermore, if one can predict that the bathymetry has not changed by more than 60% locally, from the data in the existing data set, the RMS

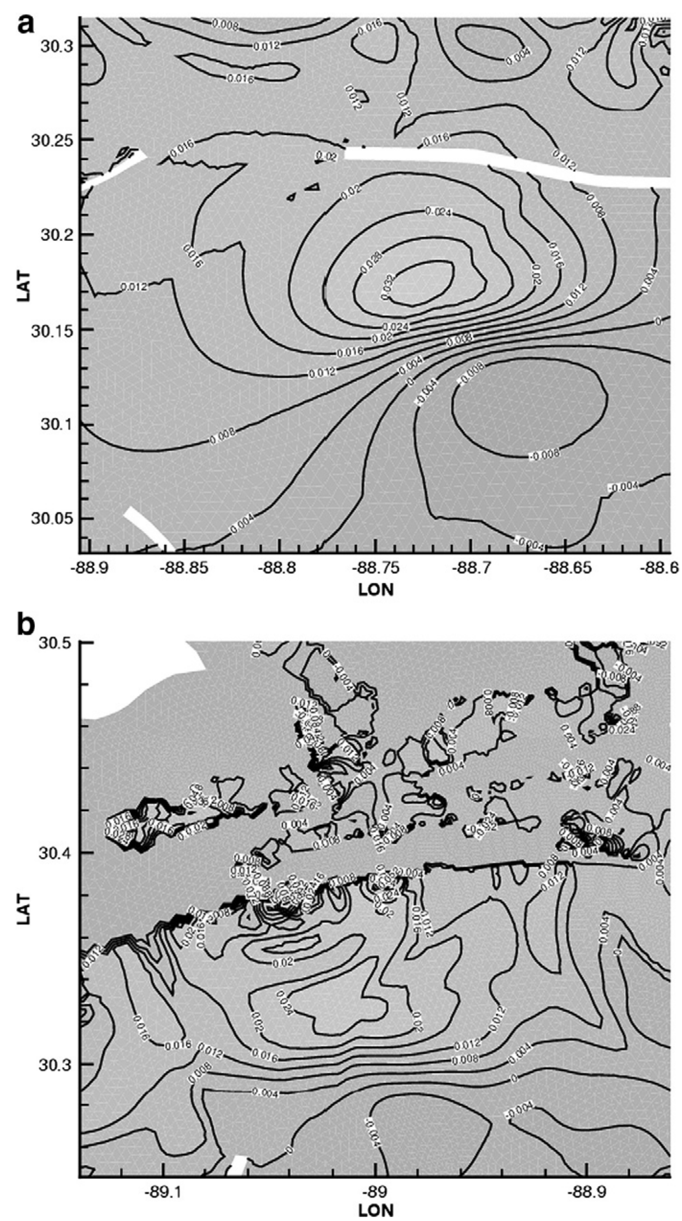

Fig. 14. Difference plot of the surge on the altered bathymetries for Mississippi coast. a) Shows the comparison at the 15 m contour. b) Shows the comparison at the 5 m contour. Both plots show the differences in surge response of a +20% and −20% variation in the bathymetric contours to hurricane Katrina forcing. X and Y axis units are in degrees Longitude and degrees Latitude respectively. Contours are labeled with units of meters.

difference in the surge at the coast will be within 4.59%. There is no benefit from expensive repeated surveys beyond the depth at the distance of relative influence.

Our tests indicate that this cut-off depth is approximately 30 m, and the distance will vary with average slope near the coast. This cut-off is well within the limits of current LiDAR technology even when the water clarity is not perfect. These tests also show that knowing the bathymetry in shallow waters can make a large difference in the results. We find that as the perturbations occur closer to land, the response at the coast becomes more significant.

Shoreward of this depth of relative influence, (DRI), we saw the greatest differences between the computed surge for the perturbed and unperturbed profiles. Outside the DRI the local changes in bathymetry are negligible, as the relative surge at the coast goes to one.

The 2D results followed the expectations derived from the 1D test study. The sites for the 2D tests had slopes that ranged from 1:1700 (Mississippi Coast) to 1:50 (Florida Panhandle near the coast). We forced 20% fluctuations in the bathymetric profile both up and down and recorded the differences. Consistent with the 1D test results as illustrated in Fig. 7, the 2D results of the surge from the shallow variation and the deep variation lie within 2% of each other. This translates to a less than 2% difference from the unaltered bathymetry. The 1D results show that a $\pm 20\%$ fluctuation in bathymetry will result in no more than a $\pm 5\%$ variation in surge, and the bulk of the results are within $\pm 2\%$.

Good bathymetry is important to accurately predicting both waves and surge. Perfect knowledge of the local bathymetry cannot be obtained. As with any simulation or project the investigator must set the limits on errors. Even after the best of attempts to collect a data set, the resulting representation will have errors. This is due, in part, to the fact that the sea floor is constantly changing, as well as imprecision in the data collection techniques. This study offers an estimate of the error from incomplete or imperfect knowledge of the bathymetry.

As long as the large scale coastal bathymetric characteristics such as widths and slopes are known, the fine small scale deviations can vary locally without disrupting the surge results by more than 10% RMSD, and often by much less as shown in our 2D case study. There are many sources of small percentage (and even larger percentage) error in every model. Knowing those errors is an important part of understanding what the model results are conveying. If your model already has errors from forcing terms or assumptions/simplifications of the physical formulas, then perhaps a possible 5%–10% RMS error from imperfect knowledge of the bathymetry is well within the range of already assumed errors that arise elsewhere. A lengthy expensive project to collect more exact bathymetric data may not be very helpful in improving model accuracy, especially if the current data set available is deemed to be acceptable by the investigators.

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