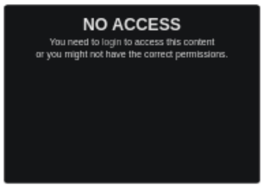
# Wetland Dynamics and Morphological Changes due to Hurricane-induced Sediment Deposition

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  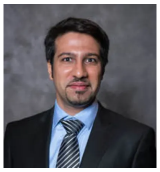 

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# INTRODUCTION

Wetlands are endangered ecosystems that provide valuable services to society and contribute to maintaining biodiversity in low-lying areas. Hurricanes, among other stressors such as sea level rise (SLR) and anthropogenic activities, alter wetland dynamics and shape coastal morphology by redistributing sediments in estuaries and bays. Specifically, hurricane forcing is responsible for sediment deposition and erosion within coastal wetlands and their surroundings [1].

Coastal wetlands (e.g., salt marshes) cope with SLR by controlling the overall sediment balance of the marsh platform (e.g., release or storage of sediments) [2]. Sufficient sediment/nutrient supply and inundation duration enable the marsh platform to accrete and keep pace with rising water levels (Figure 1). As indicated in the figure, fully exposed marshes are characterized by negligible inundation duration in a tidal cycle that limits sediment deposition and/or marsh accretion (e.g., balance of sediment deposition, erosion, and compaction processes) [3]. Theorethically, the highest rate of marsh deposition would occur for an inundation duration equivalent to half of the tidal cycle [4]. Fully inundated marshes are those permanently flooded in the tidal cycle as a result of SLR and insufficient sediment input for the marsh platform to accrete. Those marshes will be eventually transformed into mudflats or open water [3].

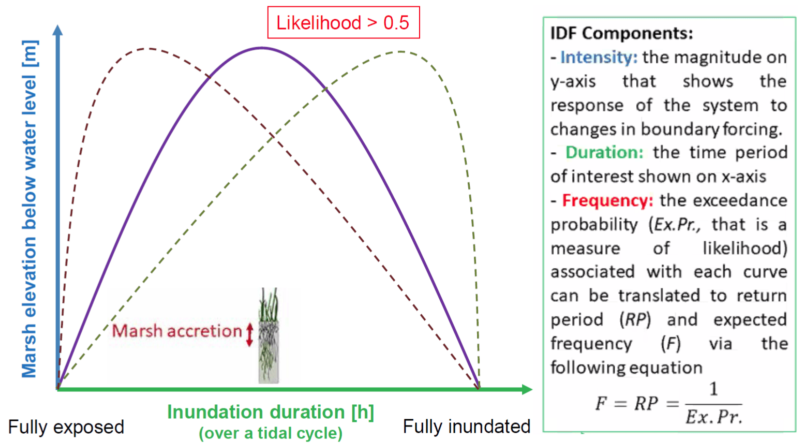


**Figure 1.** Theoretical inundation duration and likelihood of marsh deposition/accretion and marsh platform erosion.

The objective of this study is to reconcile theoretical curves (Figure 1) with both spatiotemporal patterns of wetland coverage change (i.e., wetland loss and gain) and hydrodynamic simulations of average (normal) and extreme (hurricane-like) scenarios in Mobile Bay, AL, U.S. Understanding hurricane-induced sediment deposition and erosion is crucial for resource managers and researchers to develop wetland protection and/or restoration programs.

## STUDY AREA

Mobile Bay (MB) is located in southwestern Alabama, U.S. In terms of freshwater influx, MB is the fourth largest estuary in the Continental United States with a mean daily freshwater discharge of 1715 $m^3/s$ [5]. The bay has a surface area of 1070 $km^2$, length of 50 km, maximum width of 39 km, and a mean depth of 3 m. MB debouches into the Gulf of Mexico through a narrow inlet that separates Dauphin Island and Fort Morgan Peninsula (Figure 2). Freshwater discharge at the head of the Bay is attributed to the Tensaw River and Mobile River, which convey ~95% of the freshwater inflow [6]. The MB watershed comprises Bon Secour Bay (southeast) and the Gaillard Island (northwest) created with dredged material in 1979. Weeks Bay located southeast of MB is a protected tributary estuary that was designated as National Estuarine Research Reserve (NERR) in 1986.

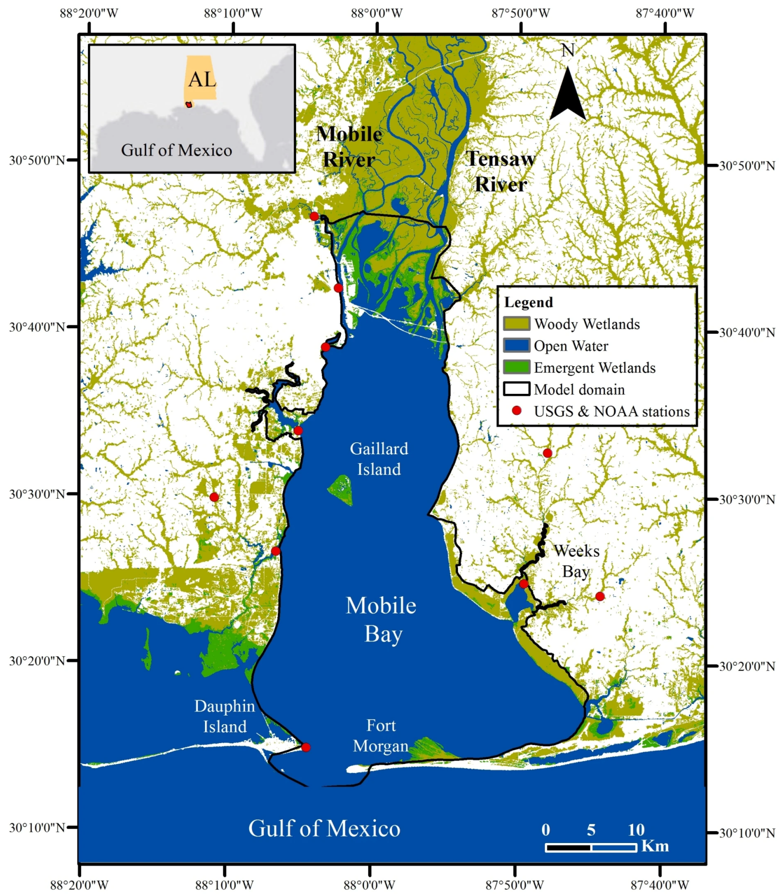


**Figure 2.** Map of Mobile Bay, AL and wetland coverage derived from multisource remote sensing imagery [8]. Model domain is outlined with a black polygon whereas gauge stations used for model calibration and forcing data are shown with red circles.

# METHODS

### Hydrodynamic modeling

We developed and calibrated a two-dimensional (2D) model of MB in Delft3D-FM to simulate water level variability and estimate inundation duration in coastal wetlands (Figure 3). The model accounts for a set of boundary conditions (BCs) including river discharge, precipitation, coastal water level, local wind and atmospheric pressure obtained from the U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and reanalysis data (ERA-5).The calibrated model was then used to simulate two extreme events that caused elevated water levels and large flood extent in the Gulf of Mexico; namely Hurricane Ivan in September, 2004 and Hurricane Katrina in August, 2005 (Figure 3). Likewise, we simulated additional scenarios using mean river flow and predicted tides corresponding to both extreme events. These scenarios are a baseline for comparison purposes of sediment deposition and marsh platform erosion between extreme and average scenarios.

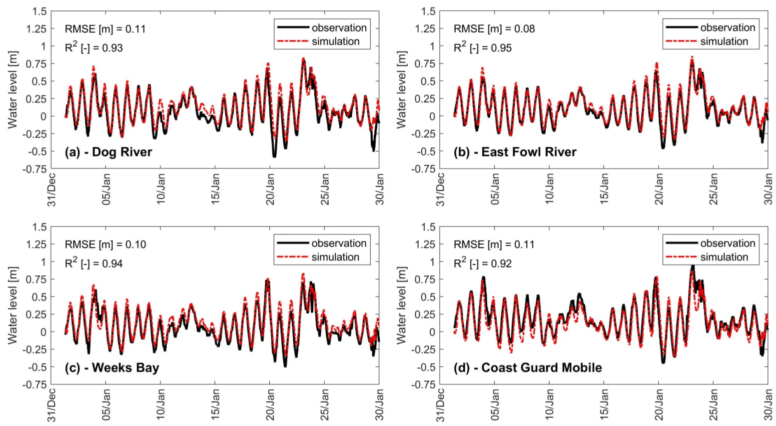


**Figure 3.** Model calibration of high and low water levels in Mobile Bay, AL.

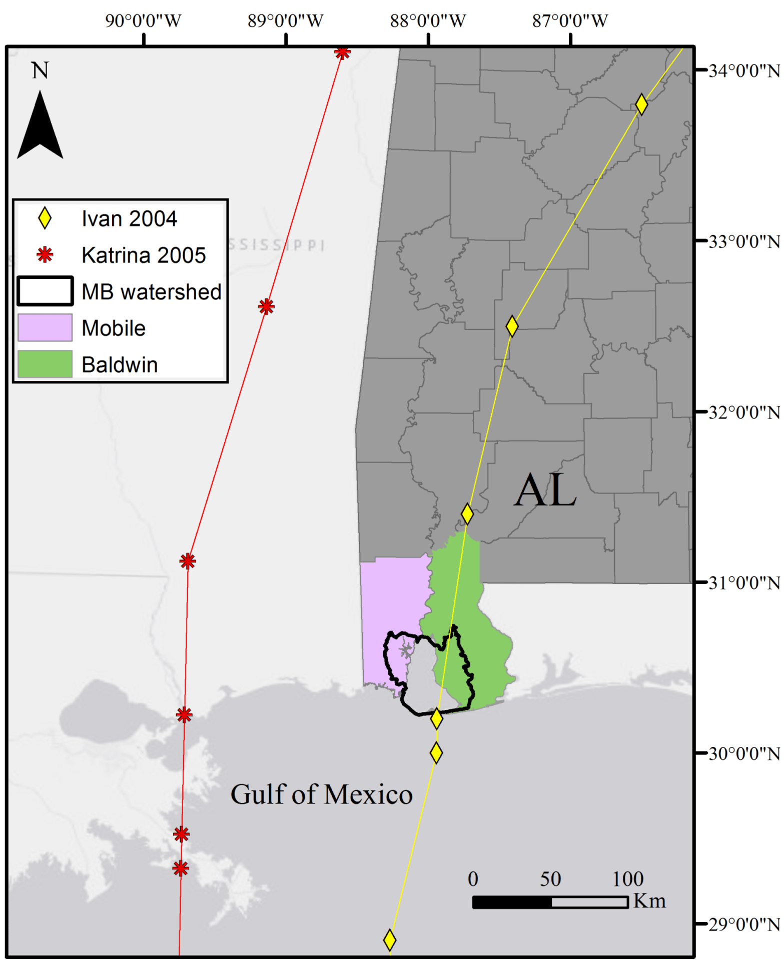


**Figure 4.** Hurricane's best tracks of Ivan and Katrina that hit Mobile Bay, AL. Adapted from [8].

### Inundation duration, wetland coverage change, and wetland elevation analysis

We identified wet and dry areas using a threshold value of 5 cm [7] over a half-hour temporal interval. We then aggregated each temporal analysis within a diurnal tidal cycle (~25-h) and estimated the inundation period (median value) for wetland regions under both extreme and average scenarios. To estimate sediment deposition and marsh platform erosion within wetlands, we used land cover change maps associated with Hurricane Ivan (2003 - 2004) and Hurricane Katrina (2005 to 2006) in addition to ‘generic’ LiDAR-derived Digital Elevation Models (DEMs) corrected for wetland elevation error, i.e., vertical bias [8]. The corrected DEMs can be seen as a proxy of historical elevation maps that allow for wetland elevation analysis where positive values indicate marsh deposition over exisiting and new 'wetland gain' regions and negative values suggest marsh platform erosion over 'wetland loss' regions. We associated changes in wetland elevation (e.g., median value) and wetland coverage to inundation duration and estimated the likelihood of wetlands to be either fully exposed or inundated. Lastly, we conducted a frequency analysis of inundation time versus elevation change using histograms and fitting a probability density function (PDF) to the data (e.g., non-parametric kernel function).

# RESULTS AND DISCUSSION

## Hurricane-induced sediment deposition and marsh platform erosion

Spatial analyses of wetland elevation change between extreme (hurricane-like) and average scenarios show positive (green) and negative (red) values above 0.25 m and below -0.25 m, respectively (Figure 5). Note that many wetland regions in MB are highlighted with red color suggesting a dominant erosion pattern (e.g., wetland loss) in shorelines as compared to sediment deposition in inland areas.

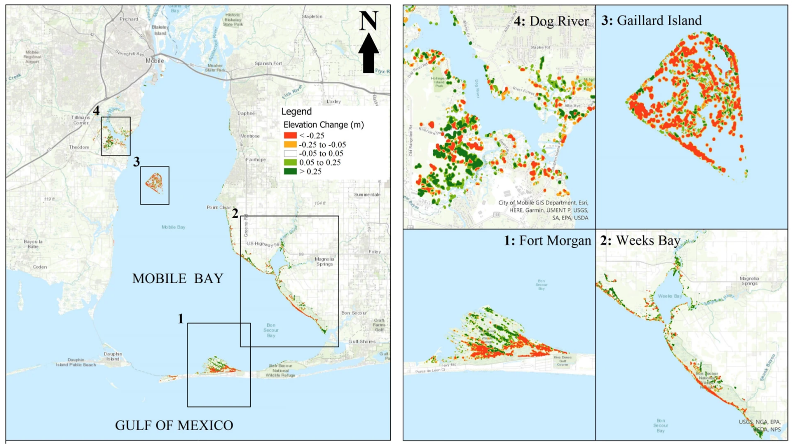


**Figure 5.** Spatial distribution of wetland elevation change in Mobile Bay, AL.

A more comprehensive analysis of wetland elevation change versus inundation duration indicates that the maximum likelihood of sediment deposition peaks around 4-h and 7-h for average scenarios, and around 6-h and 7-h for extreme scenarios. Likewise, the maximum likelihood of marsh platform erosion peaks around 11-h and 16-h for average scenarios, and around 6-h and 21-h for extreme scenarios.

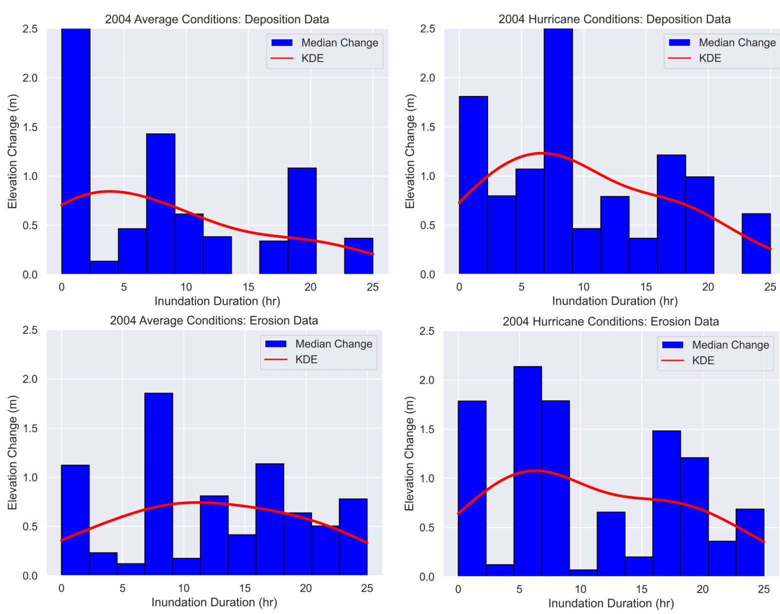


**Figure 6.** Likelihood of sediment deposition and marsh platform erosion for average scenarios (left panel) and Hurricane Ivan (right panel).

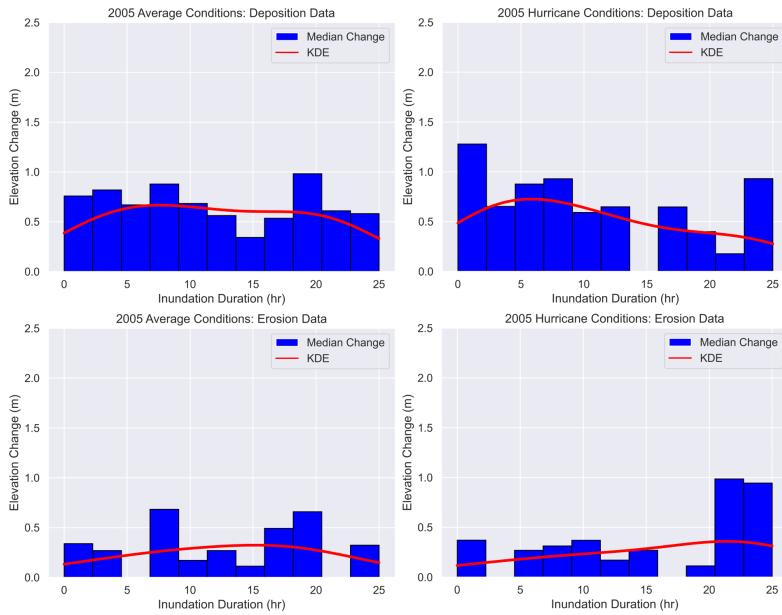


**Figure 7.** Likelihood of sediment deposition and marsh platform erosion for average scenarios (left panel) and Hurricane Katrina (rigth panel).

## Likelihood of sediment deposition and marsh platform erosion

The PDFs of sediment deposition for both average and hurricane-like scenarios show a positive skew and peak around the first quarter of the tidal cycle. This may suggest a surplus of nutrient and sediments from fluvial discharge that helps the marsh platform to accrete especially in inland regions. In that regard, coastal wetland studies in Weeks Bay estimated a seven-fold increase of salt marsh coverage by the end of the 21st century due to suitable topography and sufficient sediment input and nutrients from the Fish and Magnolia Rivers [9].

Likewise, the PDFs of marsh platform erosion for both average scenario and Hurricane Ivan show a positive skew and peak between the first and second quarter of the tidal cycle. In contrast, the PDFs for both average scenario and Hurricane Katrina show a negative skew and peak around the third quarter of the tidal cycle. Such differences of inundation duration and marsh platform erosion may be attributed to complex interactions between hurricane forcing, sea level rise, and urbanization that exacerbate wetland loss in MB. Although the hurricane's best track of Ivan was closer to MB than that of Katrina (Figure 4), wetland net loss associated with Ivan (4 $km^2$) was estimed to be 14 times smaller than that attributed to Katrina (56 $km^2$) [8].

# CONCLUSION

In this study, we matched theoretical curves of marsh deposition and erosion with both spatiotemporal patterns of wetland coverage change and hydrodynamic simulations of average and hurricane-like scenarios in Mobile Bay, AL, U.S. For this, we conducted wetland elevation change analyses as a proxy of sediment deposition and marsh platform erosion. Results revealed that Hurricane Ivan and Katrina had a two-sided effect on Mobile Bay's coastal wetlands: (i) erosion along shorelines and marsh edges due to extreme coastal water levels and strong winds, and (ii) sediment deposition in landward direction due to both hurricane-induced sediment deposition and fluvial sediment input.

We also showed that the maximum likelihood of sediment deposition in Mobile Bay peaks between the first and second quarter of a diurnal tidal cycle (~25-h). In contrast, the maximum likelihood of marsh platform erosion is highly dependent on the hurricane forcing characteristics as well as the complex interactions among hurricanes, sea level rise, and urbanization. Nevertheless, additional simulations of average and extreme scenarios next to field measurements of marsh deposition and erosion are needed to support these conclusions.

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## ABSTRACT

Wetlands are endangered ecosystems that provide valuable services to society and contribute to maintaining biodiversity in low-lying areas. Hurricanes, among other stressors such as sea level rise (SLR) and anthropogenic activities, alter wetland dynamics and shape coastal morphology by redistributing sediments in estuaries and bays. Hurricane forcing plays a key role in sediment deposition and erosion within coastal wetlands and their surroundings; hence maintaining marsh elevation relative to SLR as well as eroding the edge of marsh platforms. In this study, we reconciled observed spatiotemporal patterns of wetland coverage change from multi-source remote sensing imagery with hydrodynamic simulations of both average and extreme (hurricane-like) scenarios in Mobile Bay, AL, USA. To account for sediment deposition and erosion in coastal wetlands, we constructed 'generic' LiDAR-derived digital elevation models (DEMs) corrected for wetland elevation errors (vertical bias) and used them as a proxy of historical DEMs. We then associated changes in wetland elevation and coverage to inundation duration and estimated the likelihood of wetlands to be either fully exposed or inundated in both scenarios. Results indicated that the likelihood of sediment deposition peaks between 4-h and 7-h of inundation for both average and extreme conditions. The likelihood of erosion for average conditions peaks between 11-h and 16-h, whereas that of extreme conditions is highly dependent on hurricane forcing characteristics and peaks around 6-h in the case of Hurricane Ivan (Sep/2004) and 21-h for Hurricane Katrina (Aug/2005). Results revealed that Hurricane Ivan and Katrina had a two-sided effect on Mobile Bay's coastal wetlands: (i) erosion along shorelines and marsh edges due to extreme coastal water levels and strong winds, and (ii) sediment deposition in landward direction due to both hurricane-induced sediment deposition and fluvial sediment input. We acknowledge that, next to hurricane forcing, an increase in sea levels could also affect sediment dynamics and so alter coastal morphology and compromise wetland survivability.