NUMERICAL MODELLING OF STORM-DRIVEN SEDIMENT TRANSPORT IN CURRITUCK SOUND, NC

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Abstract: Storms such as hurricanes generate large storm surges and surface waves in typically low-energy estuarine environments. This enhances sediment transport and affects morphology, impacting navigation and aquatic vegetation. To better understand and predict these impacts, a numerical model corresponding to a 20 km long section of Currituck Sound, a narrow back-barrier estuary in North Carolina, was implemented with a 25 m resolution using Delft3D-SWAN for two 2016 tropical cyclones. Model results compare well with observations from instrumented platforms for both waves and water levels, and the simulated bed shear stress qualitatively matched observed trends in turbidity with considerable spatiotemporal variation. Satellite observations of red and infrared reflectance indicate considerable differences in total suspended matter between the two storms despite similar peak wind speeds. These preliminary results indicate detailed in situ observations and high resolution coupled numerical models can be used to quantify estuarine sediment transport during cyclonic storms.

Introduction

Storms can generate strong surface waves and currents with the potential to transport sediments in otherwise low-energy estuarine environments. However, given the high variability in sediment types, estuarine morphology, and storm conditions, the overall response of estuaries to storms is poorly understood (Miles *et al.*, 2015). Improving the understanding of sediment transport during storms is therefore important as it influences the morphology and many economic (e.g., dredging, navigation) and environmental (e.g., aquatic vegetation, benthic habitat) issues. Estuarine systems are common coastal ecosystems along the U.S. Atlantic and Gulf coasts, and act as a region of water and sediment exchange between terrestrial and ocean environments. Estuaries are complex environments affected by numerous processes, including physiochemical reactions, waves, currents, and density gradients (Corbett *et al.*, 2007). Back-barrier estuaries are a specific type of estuarine environment characterised by a shallow bay that is commonly parallel to the shoreline and open to the ocean via inlets between barrier islands. While these inlets limit the tidal influence, water levels can vary considerably due to wind and pressure forcing and wave setup (Mulligan *et al.*, 2015a.

Hydrodynamic numerical models can be used to better understand the impact of storms on estuarine morphology. Numerical models can simulate the temporal and spatial variations in the conditions that are present during storms, allowing the quantification of sediment transport (Lin *et al.*, 2007). The ability to model estuarine processes at high resolution enables improved understanding of natural hazards that can help to reduce risks to coastal regions. As an example, Beudin *et al.* (2017) simulated the response of Chincoteague Bay in MD/VA to Hurricane Sandy using the COAWST model and emphasised the importance of spatial variability in modelled water levels to account for wind effects, also finding that significant areas of the estuary experienced bathymetric changes. In the large estuarine system in NC, Mulligan *et al.* (2015a) simulated the waves and storm surge from Hurricane Irene using the coupled Delft3D-SWAN wave-current model and emphasised the importance of incorporating waves in hydrodynamic models to determine storm impacts on estuaries. In the present study the response of Currituck Sound, a back-barrier estuary connected to the larger NC estuarine system, to two different tropical cyclones is investigated using in-situ measurement from observation platforms and a numerical model that resolve a local (20 km long) region in high resolution.

Currituck Sound

The Albemarle-Pamlico Estuary System (APES) in North Carolina (Figure 1) is the second largest estuarine system in the United States and is key to the economy of the region. Typical of back-barrier estuaries, the system is shallow, with an average depth of approximately 5 m, and is characterized by muddy to sandy sediments. Inflows enter primarily through four rivers, and outflows occur through three major inlets in the 260 km long Outer Banks barrier island chain. Ecological and sediment studies have indicated that the APES is strongly influenced by storm events (Mulligan *et al.* 2015a; Clunies *et al.*, 2017) and morphological changes can occur rapidly under fluctuating hydraulic energy conditions (Paerl *et al.*, 2006). Storms also impact the sediment resuspension and nutrient cycling, likely influencing fisheries productivity (Giffin and Corbett, 2003; Corbett, 2010). Currituck Sound (CS) is the northernmost segment of the APES. It is approximately 58 km long, varies in width from 5-13 km, and has a mean depth of 1.5 m. Without an inlet directly connecting it to the ocean, it is microtidal (Moran *et al.*, 2015), and wind mainly controls water level fluctuations.

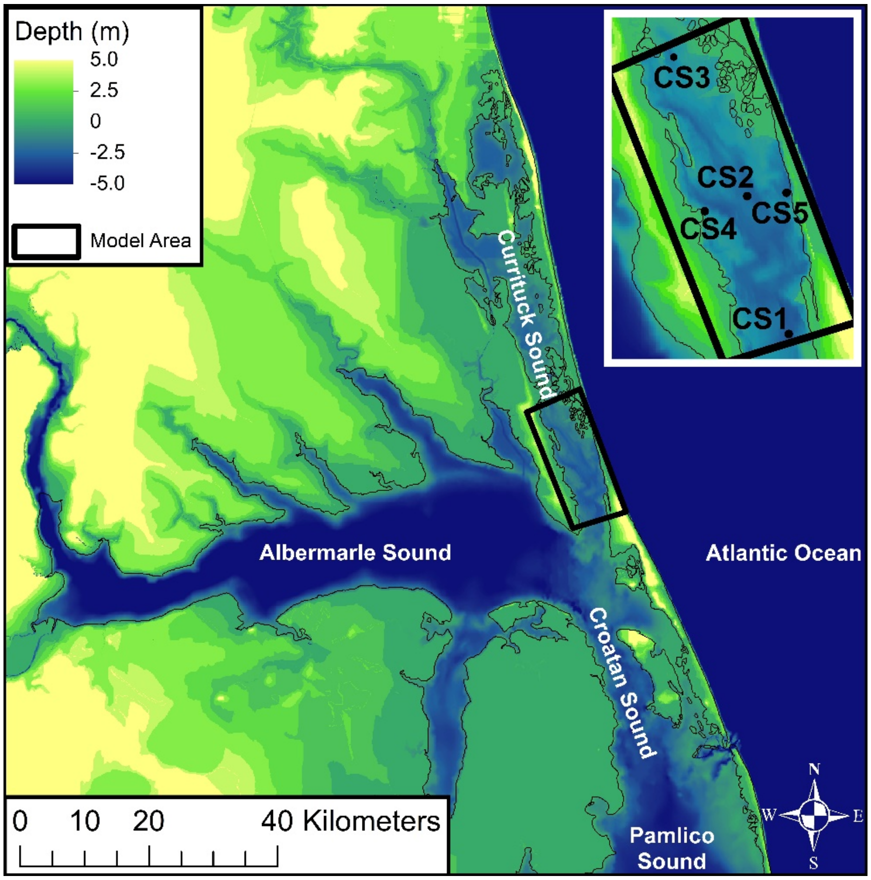

Fig 1. Bathymetry of the northern portion of the APES including Currituck Sound, with the model domain indicated by the black box. Inset indicates the USACE monitoring platform sites (CS1-CS5).

Observations

Data was collected by the US Army Corps of Engineers (USACE) using sensors mounted on five observation platforms (CS1-CS5) in Currituck Sound, shown in Figure 1, from January 2016 to January 2018. The observations include winds, water levels, waves, currents, and turbidity from an array of sensors on each platform. Two tropical storms occurred during the monitoring period: Tropical Storm (TS) Hermine and Hurricane (H) Matthew. TS. Hermine formed on August 28, 2016, reaching category 1 hurricane strength before making landfall in Florida. After weakening to a tropical storm, Hermine passed within 40 km of the study area on September 3 on a northwest track between Albemarle Sound and

Pamlico Sound. Hermine delivered sustained winds of 30 m/s over the study area, as well as significant rainfall (Berg, 2017). H. Matthew formed on September 28, 2016 and reached category 5 strength on October 1 near Haiti. Travelling offshore and along the US east coast, Matthew reached the study area as a category 1 storm on October 9 before dissipating on October 11. The hurricane passed approximately 200 km to the south of the study travelling east, registering sustained winds of 34 m/s near the study area (Stewart, 2017). Notably, neither storm had a significant impact on the ocean side of the Outer Banks barrier island separating Currituck Sound and the Atlantic Ocean.

For these storms, remotely sensed data was collected by the MODerate-resolution Imaging Spectroradiometer (MODIS) sensors on the NASA Aqua and Terra satellites. These sensors observe the entire earth daily in 36 spectral bands from 0.4 to 14.4 µm. For this investigation reflectance from bands 1 and 2 (sensing 620–670 nm and 841– 876 nm wavelengths in the red/infrared spectrum) are used to gain insight into the spatial distribution of suspended matter at the estuary surface. These bands provide a relatively high 250 m spatial resolution and have been used successfully to track total suspended matter in coastal waters (Miller *et al.*, 2004). A qualitative spatial distribution of post-storm suspended matter from 8-day averaged satellite observations are shown in Figure 2. These images clearly illustrate both the extent of the suspended material, as well as variations between the two storm events. Although both events had similar peak wind speeds over Currituck Sound, variations in wind direction, storm surge, and waves resulted in higher infrared reflectance at the estuary surface during H. Matthew.

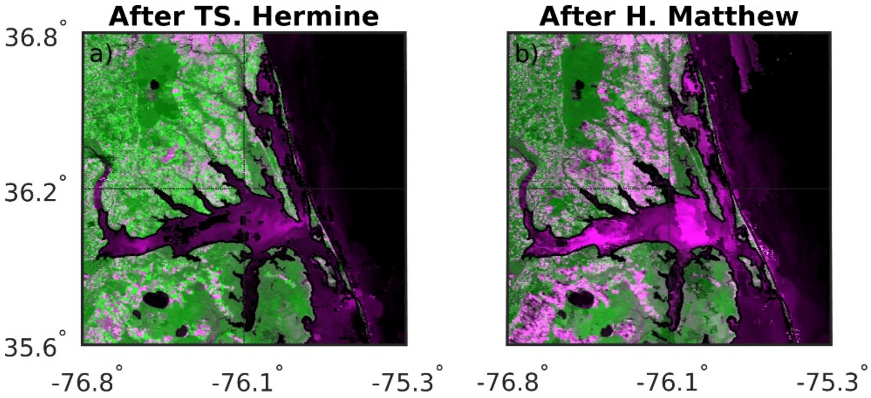

Fig 2: False-colour MODIS satellite imagery for qualitative visualizations of total suspended matter at the surface, shown in pink, averaged over: a) September 5-12, 2016; and b) October 7-14, 2016.

Time series observations at selected sites are presented in Figure 3. Both storms delivered strong winds to Currituck Sound with a rapid increase in wind speed to over 25 m/s combined with a shift in the wind direction. However, the timing and angle of the wind with respect to the long axis of the sound were different. Waves and water levels showed considerable spatiotemporal variation, with water levels falling during TS. Hermine, while higher water levels were observed during H. Matthew. A 0.5 m difference in water level across the 20 km study area occurred during both storms, indicating the importance of local winds on the spatial distribution of storm surge effects. Turbidity was measured at the bed and is shown at CS3 and CS5 in Figure 3e, with H. Matthew having higher turbidity near the center of the study area (CS5) compared to TS. Hermine, as well as a sustained period of high turbidity following the storm.

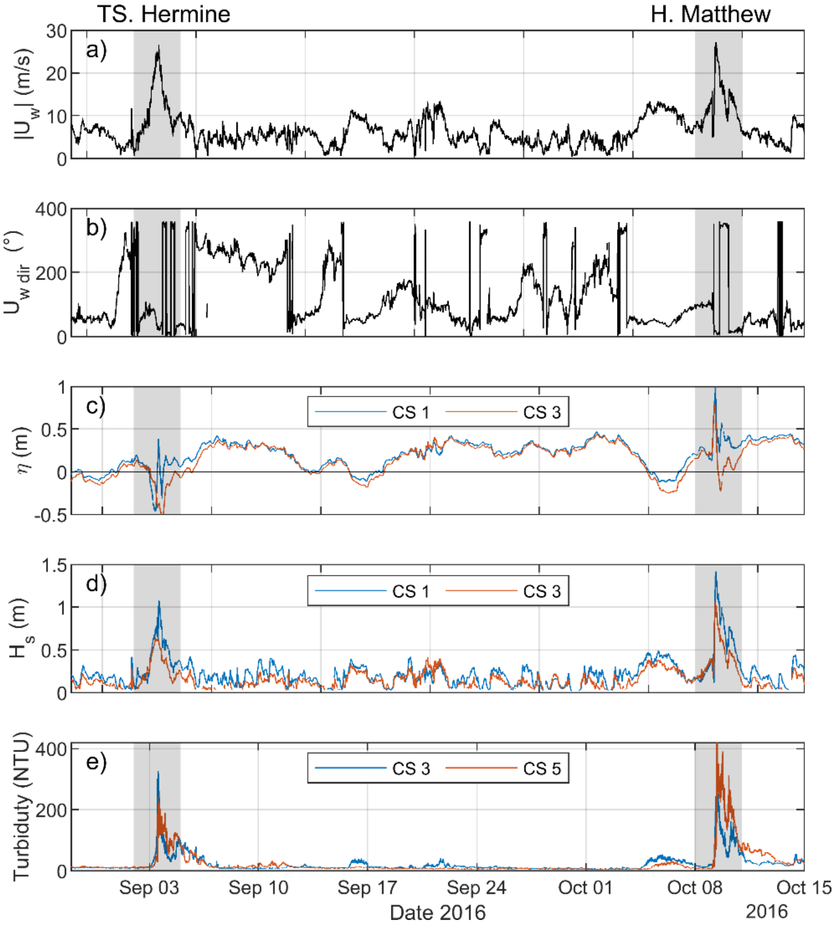

Fig 3: a)-b) wind speed and wind direction at CS4; c) water levels at south (CS1) and north (CS3) boundaries; d) significant wave height at boundaries; e) near-bed turbidity (CS3 and CS5).

Numerical Modelling

A numerical model was implemented using Delft3D, an open source, coupled hydrodynamic-wave model. Hydrodynamics, including water levels and currents, relied on the Reynolds Averaged Naiver-Stokes (RANS) equations in the Delft3D-FLOW module, described in Lesser (2004). The SWAN spectral wave model was applied as the Delft3D-WAVE module. In order to simulate spatial variability in Currituck Sound, a two-dimensional orthogonal grid with 25 m resolution was applied in the 20 km by 8 km area of the estuary shown in Figure 1. The hydrodynamic model was run in depth-averaged mode using a 12 second time step for two 3-day periods corresponding to the storm events shown in Figure 3, with waves coupled to hydrodynamics at a 30-minute interval. Model defaults were used, except for an increase of the bottom drag coefficient using the Chézy formulation ($Cz = 43\ m^{1/2}s^{-1}$) to account for increased bottom friction following Mulligan *et al.* (2015b). Boundary conditions for the "local" model domain were from observations made at the CS platforms. This includes water levels observed at the southern boundary (CS1) and the northern boundary (CS3), and bulk wave properties at the northern boundary. A spatially uniform wind field was applied using observed winds from the central observations platform (CS4) in the array.

Results

Model results are compared with observations at the CS5 platform inside the model domain (Figure 4) for water levels (η) and significant wave heights (H_s). Overall, model results were in good agreement with an average root mean square error (RMSE) of 0.07 m for η and 0.06 m for H_s as indicated in scatter plots in Figure 5. H. Matthew exhibited higher significant wave heights than TS. Hermine, as well as a rapid increase in wave heights coinciding with peak water levels. The large increase in water level with H. Matthew creates the potential for flooding in low-lying areas, influencing the potential resuspension of sedimentary material. Observed turbidity close to the bed is shown with model results for the total (wave and current) bed shear stress in Figure 4e-f.

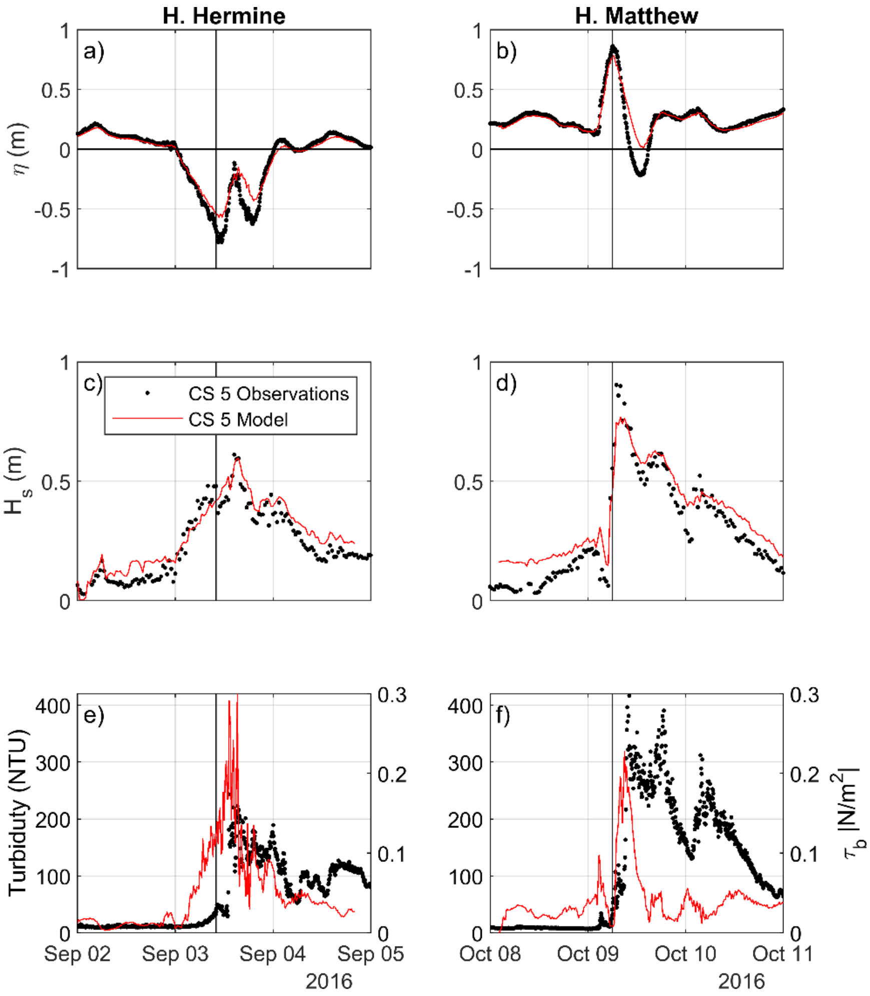

Fig 4: Storm response for a-b) water levels; c-d) significant wave heights; and e-f) suspended sediment potential as observed turbidity and model bed shear stress. Vertical lines indicate times in Figure 6.

Turbidity increased following the trends of the significant wave height and bed shear stress, suggesting that the initial increase in turbidity was a result of the storm driven resuspension. Following the peak of each storm, the simulated bed shear stress was reduced, and the observed turbidity remained elevated, suggesting advective transport from other areas. Observed turbidity was considerably lower for TS. Hermine compared to H. Matthew, corresponding with bed shear stress model results and satellite observations.

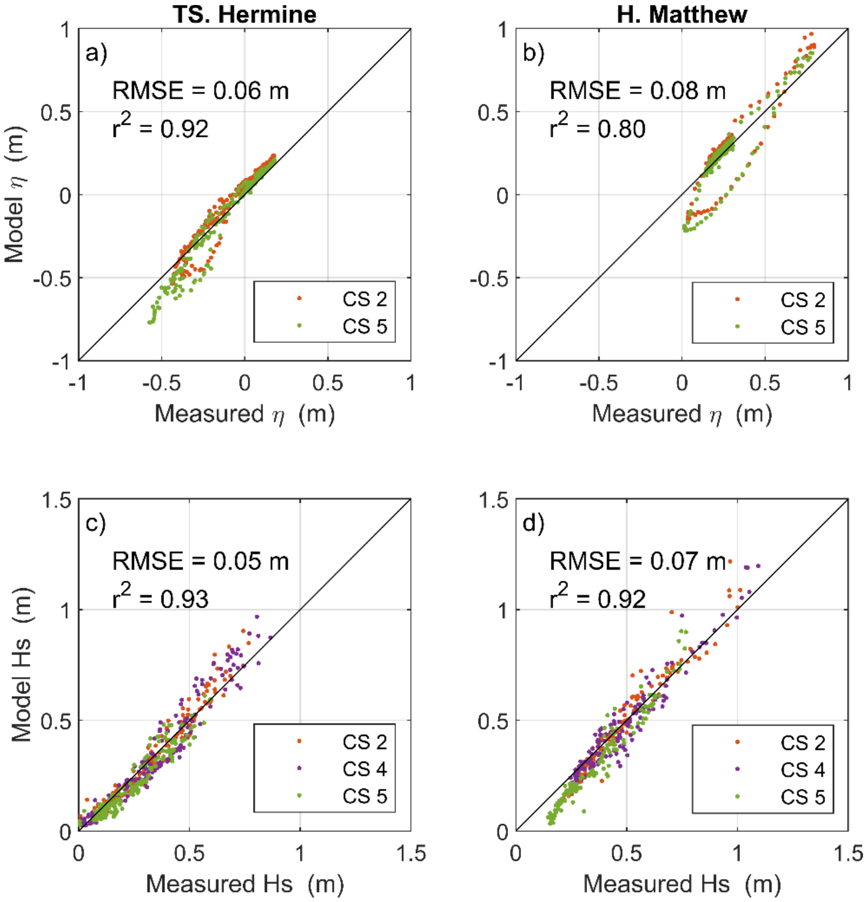

Fig 5: Scatter plots with bulk error and correlation statistics between measurements and model results for each storm event: a)-b) water levels; and c)-d) significant wave heights.

Figure 6 indicates the spatial distribution of modelled physical processes and indicates key differences between the two storms at a time step close to peak storm intensity. The higher wind-driven water levels seen in H. Matthew contributed to higher significant wave heights and enabled higher bed shear stress throughout the model domain compared to TS. Hermine, with the highest values near the southern model boundary. The effects of different wind direction on water level are also evident, with the cross-estuary wind during TS. Hermine driving water levels towards the west, in contrast to the along-estuary wind during H. Matthew.

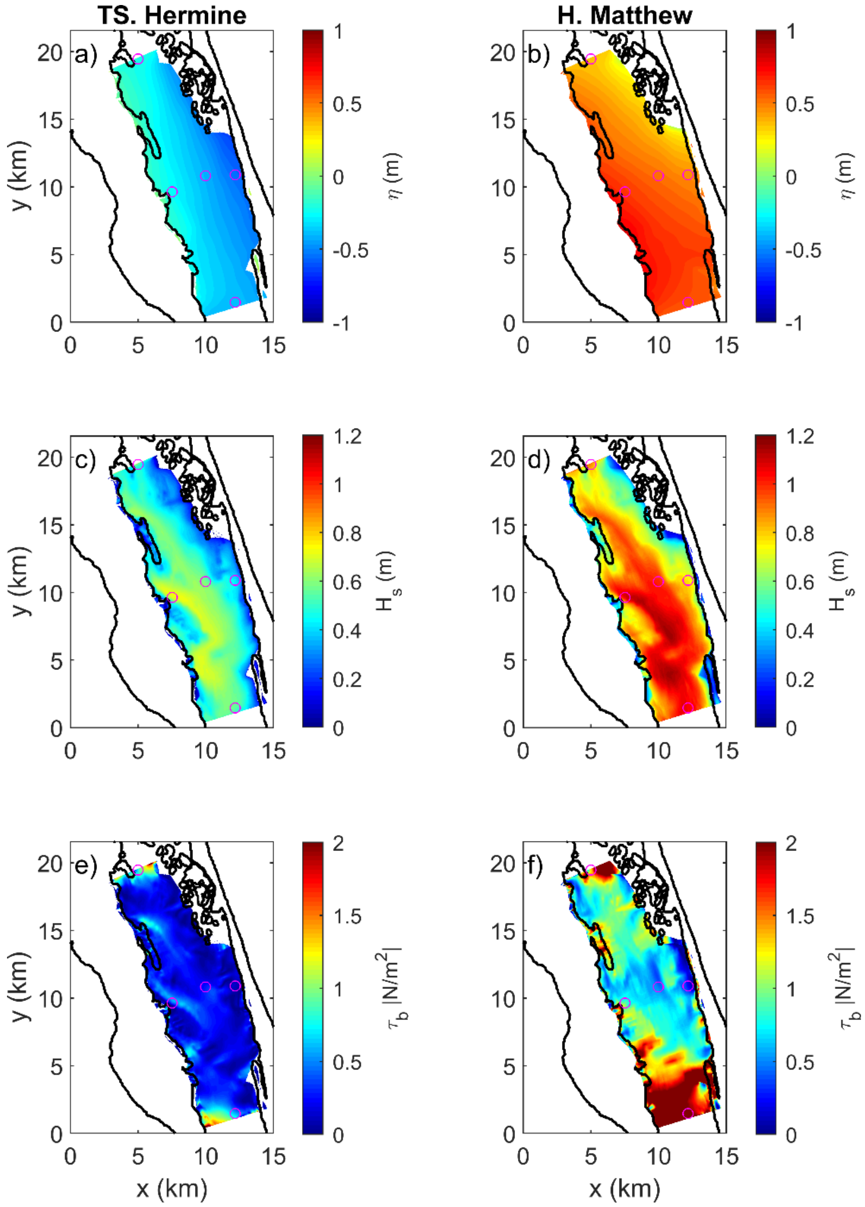

Fig 6: Model results for: a)-b) water levels; c)-d) significant wave height; and e)-f) bed shear stress on 03:00 Sept 6 for TS Hermine and 06:30 Oct 9 for H Matthew. CS1-CS5 are marked by circles.

Discussion and Conclusions

A comprehensive estuarine monitoring program was conducted at five observation platforms in Currituck Sound, North Carolina, and included measurements of waves, water levels, and turbidity. Two major tropical storms during the fall of 2016 that impacted Currituck Sound were studied to evaluate the impact of varying storm conditions on sediment transport. A high-resolution (25 m) numerical model was implemented over a local segment of the estuary (20 km long) using Delft3D-SWAN to simulate the waves and storm surges generated by winds. The model results were in excellent agreement with observed water levels and significant wave heights. Results aligned with qualitative observations using NASA MODIS imagery after each storm, indicating higher total suspended sediment after H. Matthew compared to TS. Hermine. Observations and modelling results showed considerable variation in bed shear stress between the two observed storms despite their similar peak wind speeds and initial water levels. These water levels were driven by slight changes in wind direction throughout the APES, creating very different conditions in Currituck Sound, resulting in peak storm surges in the sound that were -0.5 m (TS Hermine) and +1.0 m (H Matthew). The higher water levels during H. Matthew contributed to higher wave heights, and consequently higher bed shear stress that caused sediment resuspension from the bed. Spatial variability in waves, water levels and turbidity were also observed, with water levels varying up to 0.5 m across the short axis of the sound. These results stress the hydraulic and morphologic complexity of back-barrier estuaries. During storms, observations show that rapid and inter-dependent physical processes influence sediment resuspension and transport with high spatial variability. Additional research using three-dimensional morphological models that cover a larger region in high resolution is required to fully simulate hydrodynamic and sediment processes during storm events.

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