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# Modeling hydrodynamics of large lagoons: Insights from the Albemarle-Pamlico Estuarine System

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## ABSTRACT

Large estuaries are influenced by winds over adjacent coastal ocean and land areas causing significant spatial variations in water levels, currents and surface waves. In this study we apply a numerical model to simulate hydrodynamics and waves in the Albemarle-Pamlico Estuarine System, a large and shallow back-barrier basin in eastern North Carolina, over a one-month study period (September 2008) with observations from several storm wind events of differing time scales and directions. Model performance is evaluated for a spatially varying wind field from the North American Regional Reanalysis (NARR) dataset in comparison to spatially uniform forcing from wind observations at offshore, coastal and land-based sites across the region. A spatially uniform wind field from offshore winds observations results in statistically better hydrodynamic simulations of water levels ($R = 0.88$) in the estuaries than NARR ($R = 0.48$) after comparison with measurements and indicates the importance of strong marine winds over most of the estuary surface area.

The influence of a prominent bathymetric feature on hydrodynamics in Pamlico Sound is also investigated by numerically removing a 30 km long and 2–3 m deep shoal from the model grid and replacing it with an idealized depth of 6 m. The removal of the shoal increases water level setup by 14% at the estuarine shoreline, decreases current magnitudes by up to 40% in the shoal region and increases significant wave heights locally by up to 25% in the sound, indicating the importance of this relict geomorphic feature as a major control on the hydrodynamic response of the system during wind events. The results suggest that increasing the water depth over the shoal can lead to higher storm surges and wave heights with the possibility of increased inundation and erosion of the back-barrier and mainland coastal regions. The complex bathymetry and marine wind influence are critical input conditions for modeling large and shallow lagoonal estuaries like the Albemarle-Pamlico Estuarine System.

## 1. Introduction

Large lagoonal estuaries are common landforms found along the U.S. Atlantic and Gulf coasts (Nichols, 1989) and along the coasts of most continents. They are important systems that have dynamic geological, biological and chemical processes (Peierls and Paerl, 2010), provide habitat to marine organisms, and have great environmental and economic value (Barbier et al., 2011). Physical processes in estuaries and lagoons are driven by tides, river input, and wind stress, but each system responds differently to these forcing functions due to differences in geomorphology (Kjerfve and Magill, 1989) and the responses can be difficult to determine as they are often under-monitored. North-eastern North Carolina is home to a large system of interconnected estuaries and lagoons collectively called the Albemarle-Pamlico Estuarine System (APES), shown in Fig. 1. The lagoonal system is characterized by a mean water depth of 5 m, muddy to sandy sediments (Wells and Kim, 1989), and marine and estuarine water are exchanged through inlets. In the present, Pamlico Sound in connected to the Atlantic Ocean via three Inlets (Oregon Inlet, Hatteras Inlet and Ocracoke Inlet) which are approximately 1.0 km, 2.4 km, 2.3 km wide respectively. The number and width of inlets have a large effect on salinity levels, circulation, and bathymetry of the back-barrier system (Mallinson et al., 2008). The APES is bordered to the east by 260 km of barrier islands commonly known as the Outer Banks that enclose the low-energy back-barrier environment. The low-lying spits/islands

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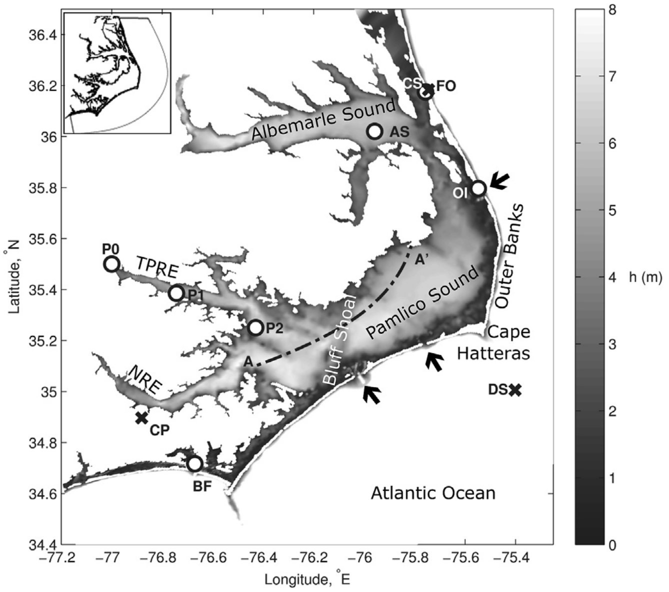

**Fig. 1.** Location of relevant places and features including hydrodynamic observations (white circles) at P0, P1, P2, Oregon Inlet (OI), Currituck Sound (CS), Albemarle Sound (AS), and Beaufort (BF). Wind observations (X's) are indicated at the Field Research Facility Ocean (FO), Diamond Shoals (DS) and Cherry Point (CP). The arrows indicate the three existing inlet locations and the curved dashed line indicates section A-A′ across Bluff Shoal in Pamlico Sound. Inset indicates the model open boundaries.

and the mainland coastal plain, less than 4 m above mean sea level (MSL), are susceptible to storm impacts from waves and storm surges that can cause island inundation and can form new inlets (Mulligan et al., 2015a). The barrier islands serve as a popular location for human activity, making island maintenance and stability a political and economic priority (Riggs et al., 2011).

Wind is the dominant mechanism that drives changes in water levels and currents in the APES (Luettich et al., 2002). Wind speeds can be very high especially at the coast (e.g. near Cape Hatteras) with strong gradients in wind speed and sea-level atmospheric pressure often associated with coastal fronts (Appel et al., 2005). In previous studies, numerical models have been used to simulate hydrodynamics of the APES. These models include: ADCIRC (Advanced CIRCulation) to investigate seiching (Luettich et al., 2002) and oyster larval transport (Haase et al., 2012); the Princeton Ocean Model (POM) to estimate density driven circulation (Xie and Pietrafesa, 1999) and storm surge and inundation (Peng et al., 2004); the Regional Ocean Modeling System (ROMS) to compute circulation and salt transport (Jia and Li, 2012); and Delft3D to investigate hurricane-generated waves and storm surge (Mulligan et al., 2015a), estuarine circulation and dissolved organic carbon transport (Brown et al., 2014), and sediment transport (Mulligan et al., 2015b). Spatially uniform wind fields have been used in numerical models of the APES (e.g., Luettich et al., 2002; Haase et al., 2012) and are typically used for small-scale (i.e., single beach) to medium-scale (i.e., lakes, estuaries, bays) numerical models. Spatially varying wind fields have been used to model cyclonic storms (e.g., Mulligan et al., 2015a; Brown et al., 2014) on short time scales. Spatial variability in the wind field and its effect on circulation have been shown to be important in lakes (Podsetchine and Schernewski, 1999), due to wind sheltering effects of surrounding shorelines and vegetation, and can drastically change circulation patterns.

The objective of this paper is to evaluate the effectiveness of a spatially varying wind field in this large, near-ocean system, and the influence of a long sand shoal on the hydrodynamics. Observations from a time period with many sensors deployed across the estuarine system are presented and coupled numerical models called Delft3D (Lesser et al., 2004) and SWAN (Booij et al., 1999) are used to simulate the hydrodynamics and surface waves. Model results are compared to observations over a one-month period with several storm events of different time scales and directions, yielding insight into the influence of wind forcing and bathymetric control on the hydrodynamics.

## 2. Observations

Observation stations for winds, water levels, currents, and surface waves for the study period in September 2008, are shown in Fig. 1. This time period was selected based on the availability of data across the region and the occurrence of two storm events that had similar wind speeds from opposing wind directions.

### 2.1. Winds

Hourly wind observations at three sites distributed geographically across the region (Fig. 1) were selected for statistical analysis. These include: 1) the US Army Corps of Engineers Field Research Facility (FRF) anemometer, which is positioned on the end of an ocean research pier 0.5 km from the shoreline (denoted FO); 2) the US National Data Buoy Center (NDBC) Station 41 025 buoy at Diamond Shoals (DS) located 26 km offshore of Cape Hatteras; and 3) the land-based Marine Corps Air Station at Cherry Point (CP) that is 24 km inland from the coast. The marine wind anemometer at FO sampled wind speed and direction at 2 Hz, with resolution of $0.1^\circ \mathrm{ms}^{-1}$ and 1.0° at 8.6 m elevation. The anemometers at DS and CP measured wind at 1.71 Hz with resolution of $0.1^\circ \mathrm{ms}^{-1}$ and 1.0° at 5.0 m and 9.0 m elevations respectively. All wind observations were adjusted to 10 m elevation assuming a logarithmic surface boundary layer (Mulligan et al., 2011). The wind speed and direction at the three stations are shown in Fig. 2, indicating that winds at the ocean-based stations (FO, DS) are very similar compared to the weaker conditions at the land-based station (CP). Two storms occurred during the month: a short duration event on Yearday 250 with southerly wind and a longer duration event on Yearday 260–269 with northerly wind (note “Yearday” indicates the day in 2008, where January 1 equals Yearday 1).

A spatially varying wind field was obtained from the North American Regional Reanalysis (NARR) dataset. NARR is a long-term, dynamically consistent, high-resolution, high-frequency atmospheric and land surface hydrology dataset with a domain that covers North America at a horizontal resolution of 32 km (Mesinger et al., 2006). It covers the period from 1979 to present at a temporal resolution of 3 h. NARR uses a sequence of steps in which the analysis from a previous time step is used as a first guess for the next time step and supplemented by inputs from the three-dimensional data assimilation (Mesinger et al., 2006) to determine atmospheric variables over 45 vertical layers. This detailed and important atmospheric data is useful in many environmental, climatological and hydrotechincal applications. In the present study we apply the results of the NARR dataset as input to a coupled hydrodynamic and wave model, and analyze the results in detail to determine the best agreement by statistical comparison with field observations. The U (oriented along lines of latitude) and V (oriented along lines of longitude) wind velocity components and atmospheric pressure (P) at an elevation of 10 m were obtained for a rectangular sub-domain of the NARR dataset covering eastern North Carolina. Two time steps of the NARR wind field are shown in Fig. 3 for Yearday 249.625 and 250.375, illustrating complex spatial structure over the APES with strongest winds typically over the ocean and eastern part of Pamlico Sound near Cape Hatteras.