Continental Shelf Research 161 (2018) 1–11

Contents lists available at ScienceDirect

Continental Shelf Research

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

A numerical model investigation of the impacts of Hurricane Sandy on water level variability in Great South Bay, New York

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ARTICLE INFO

Keywords:
Hurricane winds
Storm surge
Overwash
Ocean waves
Coastal circulation
Barrier island
SWAN
Delft3D

ABSTRACT

Hurricane Sandy was a large and intense storm with high winds that caused total water levels from combined tides and storm surge to reach 4.0 m in the Atlantic Ocean and 2.5 m in Great South Bay (GSB), a back-barrier bay between Fire Island and Long Island, New York. In this study the impact of the hurricane winds and waves are examined in order to understand the flow of ocean water into the back-barrier bay and water level variations within the bay. To accomplish this goal, a high resolution hurricane wind field is used to drive the coupled Delft3D-SWAN hydrodynamic and wave models over a series of grids with the finest resolution in GSB. The processes that control water levels in the back-barrier bay are investigated by comparing the results of four cases that include: (i) tides only; (ii) tides, winds and waves with no overwash over Fire Island allowed; (iii) tides, winds, waves and limited overwash at the east end of the island; (iv) tides, winds, waves and extensive overwash along the island. The results indicate that strong local wind-driven storm surge along the bay axis had the largest influence on the total water level fluctuations during the hurricane. However, the simulations allowing for overwash have higher correlation with water level observations in GSB and suggest that island overwash provided a significant contribution of ocean water to eastern GSB during the storm. The computations indicate that overwash of 7500–10,000 m^3s^{-1} was approximately the same as the inflow from the ocean through the major existing inlet. Overall, the model results indicate the complex variability in total water levels driven by tides, ocean storm surge, surge from local winds, and overwash that had a significant impact on the circulation in Great South Bay during Hurricane Sandy.

1. Introduction

Hurricanes are intense weather events that can generate large waves and storm surge, and cause flooding in coastal areas. The energetic wave conditions and high-water levels can drive major geomorphological changes of low-lying sandy coasts such as barrier islands, change the shape of tidal inlets, and therefore change the connections between back-barrier bays or lagoons with the ocean. Hurricane driven breaching and overwash of barrier islands has occurred recently in many locations on U.S. coasts including New Orleans during Hurricane Katrina (2005) (Fritz et al., 2007), North Carolina during Hurricane Irene (2011) (Mulligan et al., 2015), and New Jersey/New York during Hurricane Sandy (2012) (Miselis et al., 2015) as examples. The formation of a breach through a barrier island greatly impacts the hydrodynamics, morphology and water quality in back-barrier bays by changing the location and rate of exchange of water with the ocean.

The hydrodynamics of back-barrier bays are locally influenced by the bathymetry and inlets that connect it to the ocean (Aretxabaleta et al., 2014). Modelling the impacts of storms on barrier islands is a challenge as the geometry of the connections between back-barrier bays and the ocean can spatially and temporally evolve. However, numerical models are tools that can be used to help understand waves and flows surrounding barrier islands and in semi-enclosed basins in response to extreme events. For example, Miselis et al. (2015) investigated the impact of Hurricane Sandy on Barnegat Bay (NJ) using SWAN (Booij et al., 1999) and the sediment transport model (CSTM) in the COAWST modelling system (Warner et al., 2010), and determined that barrier-estuary connectivity is influenced by barrier island land use and width. Vidal-Juárez et al. (2014) predicted barrier island breaching in San Quintín, (Baja California, Mexico) due to extreme water levels using the Delft3D model (Lesser et al., 2004). Mulligan et al. (2015) used Delft3D coupled with SWAN to investigate the effect of hurricane conditions on surface wave and hydrodynamic response of a large system of connected estuaries in NC. Williams et al. (2015) used the XBeach (Roelvink et al., 2010) model results to look at site specific (west coast of Ireland) wave and water level conditions that affect dune erosion,

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https://doi.org/10.1016/j.csr.2018.04.003
Received 24 January 2018; Accepted 9 April 2018
Available online 22 April 2018
0278-4343/

overwash and breach formation.

In the present study we focus on Hurricane Sandy. This storm formed in the southwestern Caribbean Sea (Blake et al., 2013) and gained strength as it travelled northeast and parallel to the southeast U.S. coastline in October 2012. Unusual meteorological conditions caused the storm to make a westward turn that is uncharacteristic of typical tropical hurricane tracks (Halverson and Rabenhorst, 2013). Hurricane Sandy made landfall as a Category 1 hurricane on the Saffir-Simpson scale just northeast of Atlantic City, NJ, on October 29, 2012 at 2330 UTC (Coordinated Universal Time), equivalent to Yearday 303.98 (where Yearday 1 is defined as January 1, 2012). It had 36 ms^{-1} maximum sustained surface winds that caused a high storm surge along the coast of NJ and NY. The storm was nearly 2000 km in diameter with a radius to maximum wind speed up to 330 km near landfall. It is the largest storm on historical record in the Atlantic Ocean and the second costliest hurricane to hit the United States since 1900 (Blake et al., 2013) after Hurricane Katrina in 2005.

The purpose of this study is to investigate the impact of Hurricane Sandy on the hydrodynamics of the Fire Island coast and in Great South Bay (GSB) in order to understand the processes that influence the water levels the back-barrier bay. This objective is motivated by the high variability of water levels observed at gauges in GSB, the locations and details of which are discussed in Section 2. The response of GSB is estimated using coupled hydrodynamic and wave models, described in Section 3, to simulate Hurricane Sandy with a series of grids covering the western continental shelf of the Atlantic Ocean with higher resolution over Fire Island and GSB. The model is forced using tidal boundary conditions and a high resolution spatially varying hurricane wind field developed from an atmospheric model, and it is used to compute storm surge and circulation over the barrier island and in the bay. Statistical correlation of model results with water level observations are used to validate the model in Section 4 and determine the spatial variability of storm surge in Great South Bay. Analysis and discussion of the storm-driven hydrodynamics in the bay are provided in Section 5 and conclusions are presented in Section 6.

2. Study area

2.1. Location

Hurricane Sandy directly impacted Fire Island, a barrier island on the south side of Long Island, NY. This barrier system is bounded by tidal inlets called Fire Island Inlet (600 m wide, 1–10 m deep, 5 km long) at the west end and Moriches Inlet (250 m wide, 0–1.5 m deep, 300 m long) at the east end. Numerical models have been used in previous studies to investigate waves near Fire Island (Buonaiuto et al., 2011) and circulation in GSB (Wong and Wilson, 1984; Sankaranarayanan et al., 2014). Offshore of Fire Island, Goff et al. (2015) reports that Hurricane Sandy did not induce net erosion, but rather caused alongshore migration of major bedforms. However, the nearshore region of Fire Island was severely impacted during the storm with extensive overwash and erosion leading to the breaching of the island in three locations (Hapke et al., 2013). Large quantities of sand (over 50% of the pre-storm volume was lost from beach and dunes) were moved offshore or carried into the back-barrier basin. Nearly half of Fire Island was overwashed and the elevation of the beach was lowered by up to as much as 3 m in some locations (Hapke et al., 2013) resulting in dune elevations ranging from 2 m to 3 m above MSL after the storm. The western-most breach that occurred between the Atlantic Ocean and GSB is called Wilderness Breach and it occurred near the site of a historical inlet called Old Inlet, which was last open in 1825 (Flagg, 2012). The influence of geomorphic changes on water levels in GSB during Hurricane Sandy were investigated by Van Ormondt et al. (2015) using the XBeach and Delft3D numerical models, and the results suggest that overwash along Fire Island may have locally increased peak surge levels and caused the formation of Wilderness Breach.

Table 1
Observation sites used in this study.

Location	Acronym	Latitude	Longitude	Wave	Water level
New York Harbour	NYH	40.369	− 73.703	x	
Long Island	LI	40.251	− 73.164	x	
Harbour Green	HG	40.652	− 73.459		x
Captree	CT	40.659	− 73.265		x
Ocean Beach	OB	40.643	− 73.157		x
Patchogue	PT	40.749	− 73.013		x
Bellport	BP	40.752	− 72.933		x
Mastic Beach	MB	40.747	− 72.856		x
East Moriches	EM	40.787	− 72.750		x
Staten Island	ST	40.502	− 74.230		x

2.2. Observations during Hurricane Sandy

Water level sensors were deployed by the U.S. Geological Survey before the storm made landfall (Simonson and Behrens, 2015). Data from seven water level sensors (30 s sampling rate) were obtained from the Hurricane Sandy Storm Tide Mapper (Geological Survey, 2016). These were located at sites listed in Table 1 and shown in Fig. 1, and include Harbour Green (HG), Captree (CT), Ocean Beach (OB), Patchogue (PT), Mastic Beach (MB), East Moriches (EM), and Staten Island (ST). Data from a pressure sensor (6 min sampling rate) at Bellport (BP) were obtained from Flagg et al. (2016) and was converted to water surface elevation using atmospheric pressure observations from the New York Harbour (NYH) Buoy. A tidal water level gauge (6 min sampling rate) at Atlantic City (AC), located close to the eye of Hurricane Sandy at landfall, provided water level observations in the ocean relative to the Mean Sea Level (MSL) (National Oceanic and Atmospheric Administration, 2016b). All water level data that were not already at 6 min sampling (BP and AC) were converted from 30 s to 6 min using a low pass Butterworth filter. Measurements from two NOAA wave Buoys (National Oceanic and Atmospheric Administration, 2016a) listed in Table 1, at NYH and Long Island (LI), are used to determine the offshore wave conditions.

3. Numerical model

3.1. Model description

The Delft3D-Flow hydrodynamic model (Lesser et al., 2004) is used to predict flows in coastal areas solving the unsteady shallow water equations derived from the Reynolds averaged Navier-Stokes equations for incompressible free surface flow. The model can simulate currents and water levels driven by wind and wave forcing and water level boundary conditions. Delft3D-Flow is coupled to Delft3D-Wave (SWAN, Booij et al., 1999) where SWAN is a third-generation, phase-averaged wave model that uses the action balance equation to predict the evolution of the wave action density spectrum in space and time. Surface waves generated by wind are computed by SWAN, which also predicts the propagation, transformation and dissipation of wave energy. These coupled models were applied to investigate the evolution of the ocean wave directional spectrum during Hurricane Sandy described in Bennett and Mulligan (2017).

The Delft3D-SWAN model approach is useful in simulating the coupled temporal evolution of the surface wave field and water level variations due to storm surge over a large scale. A limitation of this approach is that infragravity (IG) energy cannot be simulated with these models. The XBeach model has been used in other studies to compute dune and beach erosion under hurricane conditions (McCall et al., 2010; Van Ormondt et al., 2015), and simulate the IG contribution to runup and overtopping of dunes at small scales when the dune elevations are resolved. In the present study, Delft3D-SWAN is used over a series of progressively refined grids to evaluate storm surge and