# OCEANOGRAPHIC FACTORS AND EROSION OF THE OUTER BANKS DURING HURRICANE ISABEL

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## ABSTRACT

The meteorological and oceanographic processes responsible for erosion of the Outer Banks of North Carolina during Hurricane Isabel have been simulated using a suite of numerical models. The computed wind, wave, current, and water level fields are used to drive a three-dimensional numerical sedimentation model that calculates nearshore sediment transport and erosion potential. The erosion potential is the quantity of sand that can be transported by the coastal transport system, which is the maximum volume that can be eroded. The potential erosion of the dunes is discussed by comparing the erosion potential to dune-beach volumes, which are not known in this study.

It is proposed that breaching is dependent on prior dune erosion and the difference in water levels between the open ocean and lagoon sides of the islands. Thus breaching will occur where the erosion potential is high and a large water level difference exists across the barrier island. The results are consistent with coastal erosion patterns observed in the aerial photographs taken after landfall.

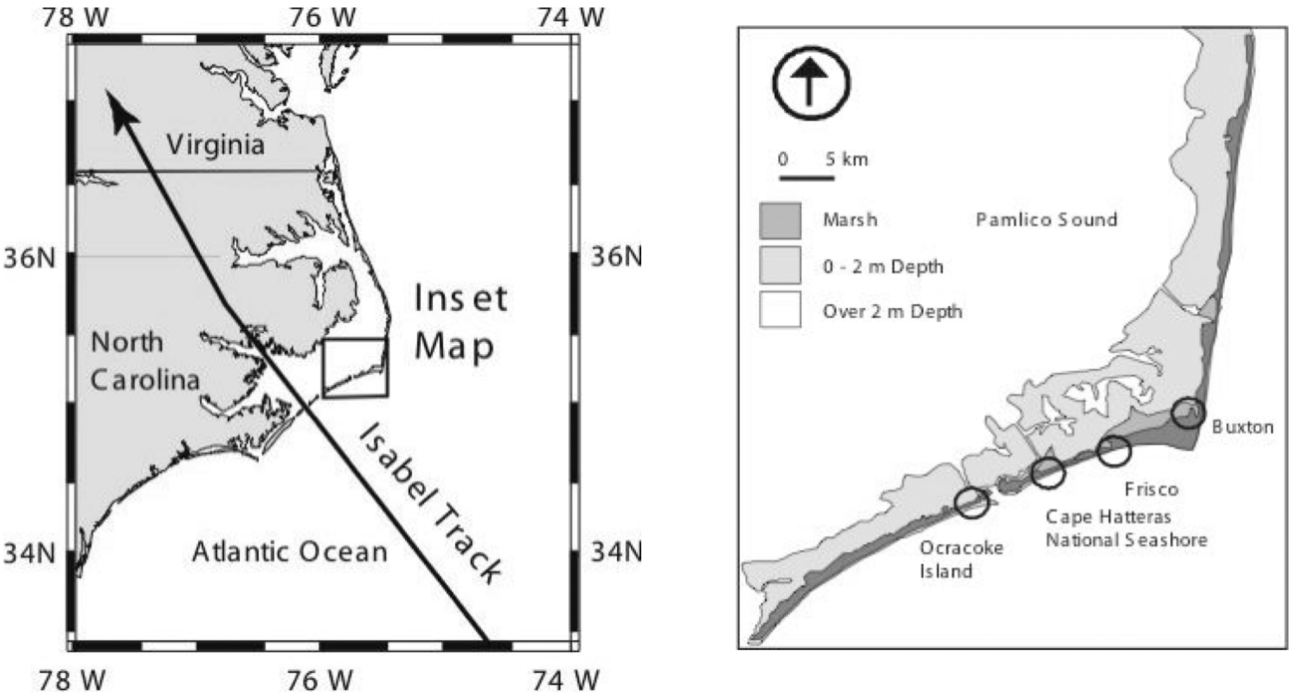

**Figure 1.** Map of the Outer Banks showing the path of Hurricane Isabel on 18 September 2003. The inset map shows the Cape Hatteras locations (circled) discussed in the text.

*K.G. Sellner (ed.). 2005. Hurricane Isabel in Perspective. Chesapeake Research Consortium, CRC Publication 05-160, Edgewater, MD.*

## INTRODUCTION

The morphological response of a barrier system to a severe storm consists of distinct erosion and deposition phases [1]. The erosion phase is characterized by dune scarp erosion, channel incision, and washout. Deposition comprises construction of perched fans, washover terraces, and sheetwash lineations. Maximum washover penetration and erosion for hurricanes occurs in the right, front quadrant within 20 to 50 km of the eye [2].

This study examines the response of the barrier islands making up the Outer Banks of North Carolina to Hurricane Isabel, which made landfall west of Ocracoke Island at 11:00 UT on 18 September 2003 (Figure 1). From what is known of barrier island response to hurricanes [3], the severe overwash and breaching of Hatteras Island during Isabel are not surprising. Nevertheless, the relationships between atmospheric, oceanographic, and sedimentological processes during hurricanes are poorly known. If the complex response of a barrier island system such as the Outer Banks is to be understood, demonstrating a direct relationship between oceanographic forcing and patterns of barrier island erosion becomes necessary.

This paper identifies these links and uses them to predict erosion patterns during Hurricane Isabel. The use of numerical models to simulate atmospheric, oceanographic, and sedimentological processes during a hurricane can reveal the causes of specific erosional responses. It remains for the coastal research community to improve this ability further through the use of more-detailed coastal erosion models that use these simulated processes to make specific predictions for future storms.

## METHODS

The National Oceanic and Atmospheric Administration (NOAA) flew several reconnaissance flights over the Outer Banks after Hurricane Isabel to assess the damage. Images were taken between 19 and 21 September with an Applanix-Emerge Digital Sensor System (DSS) mounted on a NOAA Twin Otter aircraft flying at an altitude of 1875 m (7500 ft). The ground sample distance for each pixel is approximately 0.37 m. The DSS system has a built-in GPS system that allows geo-referencing of the images [4]. The geo-referenced images were not available for this study, however; instead high-resolution jpeg images were used. The magnitude of washover penetration can be estimated from the photographs, using vehicles and road markings for scale.

The model system in this study couples individual models so that key information can be passed between them [5, 6, 7]. A parametric cyclone wind model [8] is used to calculate the wind field. The wave field is calculated by the SWAN (Simulating WAves Nearshore) wave model [9], developed for use in coastal areas. This study uses the Navy Coastal Ocean Model [10] (NCOM), to calculate coastal currents. NCOM is initialized using temperature and salinity data from a global circulation model [11], and forced with tidal elevations and transports at open boundary points from a global tide model [12]. The interaction of waves and currents near the seabed is represented using a model that calculates the combined wave and current shear stresses [13, 14] (BBLM). The BBLM is coupled to the TRANS98 sedimentation model [15], which has been applied to several sedimentation studies during severe storms [6, 16, 17, 18, 19]. The models use a cell size of 3.02 km and 3.71 km along the $x$ (easting) and $y$ (northing) axes, respectively. The hindcast interval is from 00:00 UT on 16 September to 15:00 UT on 19 September 2003. The model operation sequence is: 1) Holland wind model; 2) SWAN wave model; 3) NCOM circulation model; and 4) coupled BBLM and TRANS98 model.

A bed conservation equation is solved using the sediment transport vectors from TRANS98 [19]. Erosion is predicted at grid cells where a transport divergence results from the storm currents; converging currents result in deposition. Observations in the Gulf of Mexico and the Atlantic coast indicate that the inner shelf (deeper than about 3–5 m) is either a site of deposition or no change over long time intervals and during storms [20, 21, 22, 23, 24]. If a divergence occurs in the sediment transport field at a boundary cell adjacent to land, therefore, the eroded sand is replaced by sediment from the adjacent land point. This boundary condition assures that no erosion will occur at coastal water cells and has been implemented with the TRANS98 model for a northeaster at the Field Research Facility at Duck, North Carolina [16]. The results were consistent with measurements of bed elevation, indicating that it constitutes a reasonable first approximation of beach and dune erosion. The volume of sediment removed from the adjacent land point is referred to as potential erosion (e) in this study.

## RESULTS AND DISCUSSION

### The Morphological Response of Ocracoke and Hatteras Islands

Washover terraces and perched fans were deposited 650 m inland at the eastern end of Ocracoke Island (Figure 2a) at a distance of 50 km from landfall. Newly incised channels, in addition to dune erosion and washover deposition (Figure 2b), are evident at the western end of Hatteras Island, which is 60 km east of the storm track. At the town of Frisco on Hatteras Island, 70 km from the storm track, coastal dunes were severely eroded and washover terraces, perched fans, and sheetwash lineations were deposited 500 m from the water line (Figure 2c). Hurricane Isabel’s impacts at Buxton, just north of Cape Hatteras and approximately 75 km from the storm path, were primarily dune erosion and the construction of washover terraces and perched fans (Figure 2d) as far as 400 m inland.

### Predicted Atmospheric and Oceanographic Conditions

The predicted meteorological and oceanographic factors all reach their maximum intensities along Hatteras Island during the 12-hour period surrounding landfall. The predicted hurricane winds become easterly and strengthen to more than 20 m·s$^{-1}$ by 18 September. A peak wind speed of 35 m·s$^{-1}$ occurs just before the eye makes landfall when the wind is onshore at south Hatteras Island (Figure 3a). The hindcast waves near Hatteras Island exceed 7 m at landfall (Figure 3b), in agreement with coastal observations during Hurricane Andrew [25].

The hindcast currents along south Hatteras Island are westerly during the storm build-up and peak at more than 2 m·s$^{-1}$ prior to landfall. Due to the shift in wind direction to onshore, however, they weaken at landfall (Figure 3c) before reversing direction as the eye moves inland and the wind becomes westerly. The storm surge is superimposed on the astronomical tides and these water surface anomalies can reinforce each other if their relative timing is correct. The tidal signal dominates the regional pattern of predicted water level (Figure 3d). The storm setup extends from Ocracoke Island eastward and northward along Hatteras Island—consistent with the predicted wind field prior to landfall, which pushes water into Pamlico Sound and piles it against the coast. Low water levels are predicted in southeast Pamlico Sound because the easterly wind at landfall pushes lagoon water to the western side of the estuary.

### Barrier Island Potential Erosion

The majority of published morphological data for hurricane impacts on mid-latitude coasts demonstrates that the overwhelming response of beaches to these events is a net sediment loss [26]. Coastal dunes are typically eroded several meters during severe storms and beaches evolve to form a storm profile that stores sand on the inner shelf [1, 2]. The dune-beach system is thus the primary source of sand for the coastal transport system.

The carrying capacity of the coastal sediment transport system is the potential coastal erosion (e), which is the maximum volume of sediment mobilized by erosional processes [27, 28]. The dune erosion potential can be evaluated by comparing the cross-sectional area of the dune-beach system, $A_D = L \cdot H_D$, to the potential erosion, e, where $H_D$ is the mean height of the dune-beach system and $L$ is its width. Potentially, the dune-beach system will be removed when $A_D <$ e. When $H_D$ is unknown, as in this study, the potential for dune erosion can be estimated by calculating the average height, $H_{AC} = e/L$, that would produce a beach-dune volume that equals e. The storm surge effectively reduces the dune height by $h$; thus $H_{AC}$ is increased by the total setup $h$ (Figure 3d); $H_{AC} = H_{AC} + h$. For example, $L$ is approximately 250 m at Ocracoke, 100 m at the western end of Hatteras Island, 200 m at Frisco, and 150 m at Buxton. The predicted values of e (Figure 4) decrease eastward; consequently, $H_{AC}$ = 1.04 m, 1.58 m, 0.9 m, and 0.6 m at Ocracoke, Cape Hatteras National Seashore (a larger predicted $h$), Frisco, and Buxton, respectively. The model is capable of predicting deposition but it does not occur along this coast during Hurricane Isabel

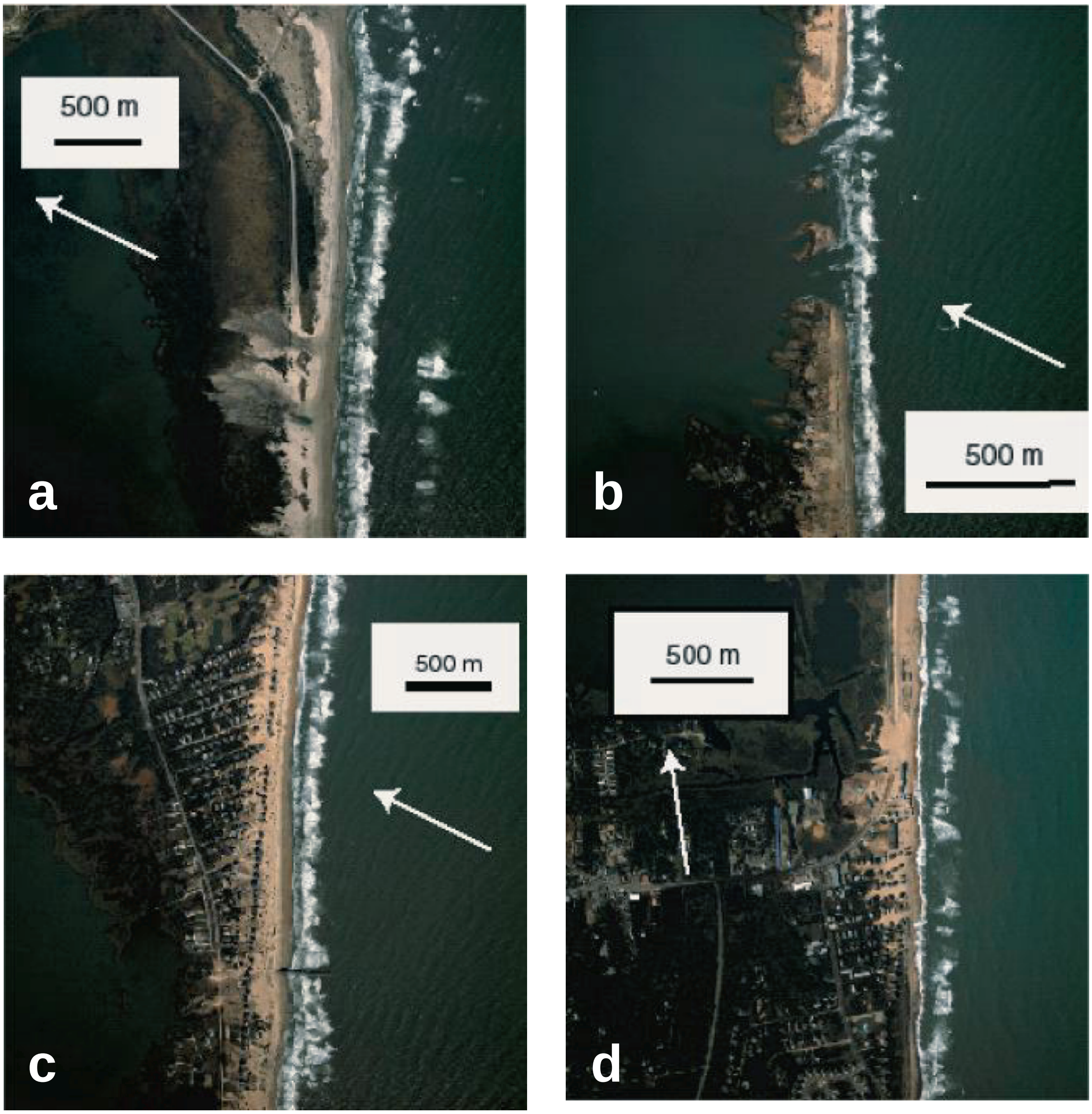

**Figure 2.** Aerial photographs taken after Hurricane Isabel on the Outer Banks: a) Ocracoke Island; b) Cape Hatteras National Seashore; c) Frisco; and d) Buxton. See Figure 1b for locations. The photographs are oriented with Pamlico Sound to the left.

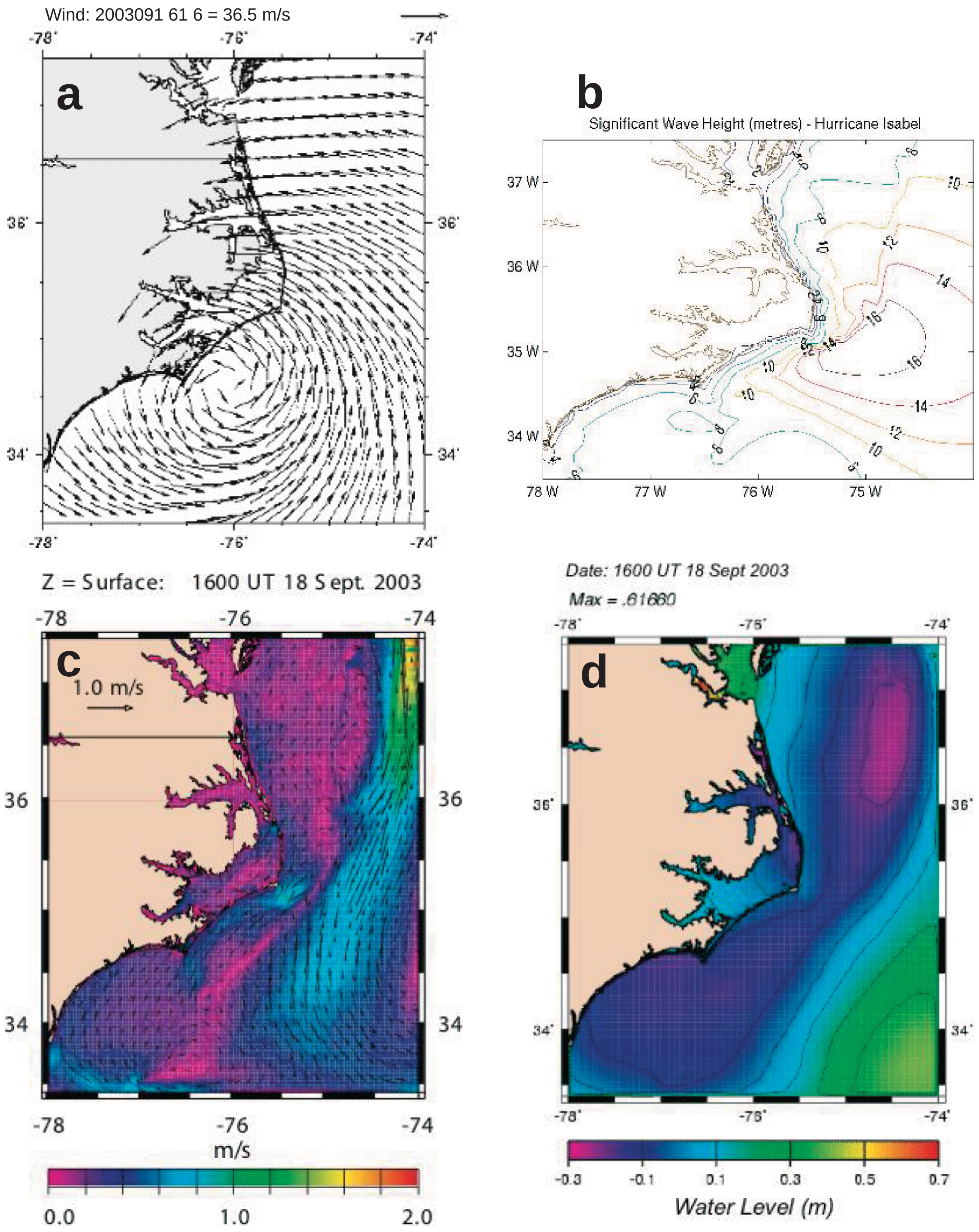

**Figure 3.** Predicted environmental conditions at landfall (16:00 UT 18 September 2003): a) The wind velocity computed by the Holland Model; b) The significant wave height from SWAN; c) The surface currents calculated by NCOM; and d) The water level anomaly calculated by NCOM (contour interval is 0.1 m).

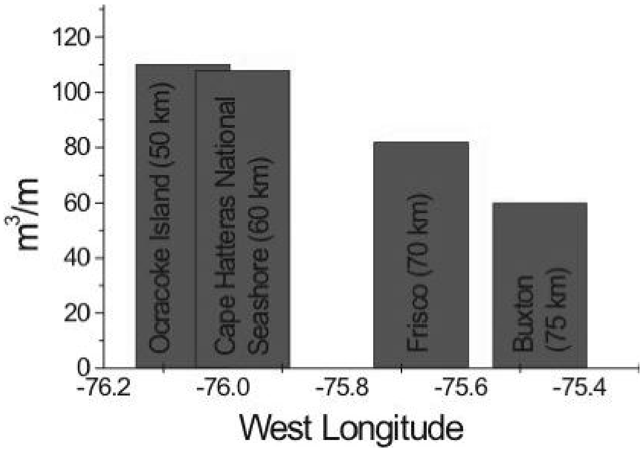

**Figure 4.** Potential erosion ($m^2$) predicted by TRANS98 during Hurricane Isabel at the locations shown in Figure 1b. The distance from landfall is given in parentheses. The units are cubic meters of sand eroded per meter of coastline.

because of the storm surge, waves, and nearshore currents.

Analysis of the available aerial photographs revealed that dune penetration was the exception at Ocracoke Island (Figure 2a), although overwash occurred locally at spatial scales below the resolution of the hydrodynamic and sedimentation models. This situation indicates that, overall, e < $A_D$ and $H_{AC} < H_D$. The lower dunes and smaller volume of sand at Cape Hatteras National Seashore would have allowed significant erosion for the same value of e as at Ocracoke. The amount of damage to the barrier island (Figure 2b) supports this conclusion and indicates that $H_D < H_{AC}$. The dunes at Frisco are as low as those at Cape Hatteras National Seashore, but coastal erosion was reduced due to its longer distance from the storm track and the greater width of the island.

The observed water levels during Hurricane Isabel (measured $h < 2$ m) did not exceed the dunes on Hatteras Island and submergence would have been unlikely. For channel incision to occur, therefore, the dune-beach system must first have been substantially eroded by waves. A second source of energy is the pressure head associated with the difference in water levels on the ocean and lagoon sides of the island. If the dunes are locally removed at weak points, this pressure gradient can drive a steady current landward, which in combination with storm waves can rapidly erode a channel to the lagoon.

The potential for breaching can be evaluated using the water level differences across the islands (Dh), the potential erosion of the dune-beach system (e), and the island width. The predicted Dh at Ocracoke at landfall is 0.65 m. Because of set-down in southeast Pamlico Sound (Figure 3d), however, the hindcast water level at Hatteras National Seashore is -1.8 m and Dh is 2.3 m. This large gradient, in combination with significant dune erosion and a narrow width (less than 250 m), caused breaching at this location. A similar pressure gradient is predicted at Frisco, but no channel was incised, partly because of somewhat lower dune erosion (e = 80 $m^2$) and greater width (more than 500 m). Although the hindcast water level inside the sound is lower at Buxton (-2.4 m), the low setup on the open coast results in a difference of 2.6 m. The dunes were entirely removed, but the width of the island prevented breaching despite a large Dh.

These results are somewhat qualitative due to a lack of beach-dune profiles, the coarse resolution of the numerical models, and the importance of several nearshore processes not included in these models, such as wave-driven flow and island inundation. Nevertheless, we consider these results robust because of their dependence on fundamental physics rather than parameterizations of diverse observations. The models predict a strong current system and large waves along the ocean side of the islands, where erosion of the inner shelf would occur if not for the supply of sand from the beach-dune sand reservoir. The comparison between the model results and the observed erosion indicates that the dunes were removed and breaching occurred in areas where this sand reservoir was insufficient. A more detailed simulation of the timing of these erosional processes will require significant additional research effort.

## ACKNOWLEDGMENTS

This work was funded by the Office of Naval Research, Program Element 61153N. The aerial

photographs of the Outer Banks were acquired from the North Carolina Geodetic Survey.

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