Numerical modeling and field evidence of coastal overwash in southern New England from Hurricane Bob and implications for paleotempestology

Kwok Fai Cheung,1 Liujuan Tang,2 Jeffrey P. Donnelly,3 Elyse M. Scileppi,4 Kam-Biu Liu,5 Xian-Zhong Mao,6 Samuel H. Houston,7 and Richard J. Murnane8

Received 23 June 2006; revised 4 March 2007; accepted 10 May 2007; published 11 September 2007.

In this paper, we examine the use of coastal overwash modeling in conjunction with geological proxy techniques to provide a more comprehensive tool for paleotempestology. Southern New England, which lies in the path of north tracking hurricanes, has been a prime location for paleotempestological studies. Hurricane Bob of 1991 is the most recent landfall in this region and has the most comprehensive data for model assessment and validation. Using the hurricane track, central pressure, and radius of maximum wind as input, a collection of four interoperable model components simulates the meteorological conditions, astronomical tides and storm surge, ocean and coastal waves, and the surf zone processes and runup onto dry land. The computed surface pressure, winds, waves, and water levels give very good agreement with data from weather stations, moored buoys, and tide gauges near the track and in the zone of maximum wind. The validated wave conditions and storm water levels define the boundary conditions for coastal overwash modeling, and the results show strong correlation with aerial photographs and sedimentary records at five sites near the landfall. The results provide modern analogs for the interpretation of early hurricane landfalls in southern New England that lack an instrumental record. Reconstruction of paleohurricanes will require geological proxy data at multiple locations for the multivariate inverse analysis with uncertain paleotopography and storm characteristics.


1. Introduction

[2] Of all natural disasters, hurricanes are the most common and cause the largest insured losses in the world [Zanetti and Schwarz, 2006]. Instrumental records of landfalling hurricanes, however, are only available for the last 150 years in the western North Atlantic [Landsea et al., 2004]. The lack of long-term records compounded with the rarity of severe coastal hurricanes results in a large uncertainty in estimates of wind speed exceedance probabilities for the extreme events [Jagger and Elsner, 2006]. These probabilities are important for a variety of activities such as emergency management, planning and zoning, and insurance underwriting.

[3] Paleotempestology is an emerging field of science that holds the promise of extending the historical records of hurricane activities by means of proxy techniques [Emery, 1969; Liu, 2004]. To date, most paleotempestological studies have been based on sedimentary data. The principal proxy used in the research is sandy overwash layers found in sediment cores retrieved from ponds and marshes behind sand barriers. These sand layers have been interpreted to be formed by overwash processes, when storm surge and waves generated by landfalling hurricanes overtop the sand barriers and deposit sand into these backbarrier ponds. Through radiocarbon and stratigraphic dating of these layers, Liu and Fearn [1993, 2000] deduced prehistoric landfall frequencies of catastrophic hurricanes in Alabama and northwestern Florida, while Donnelly et al. [2001a, 2001b, 2004a] and Donnelly [2005] documented back-barrier sedimentary records of intense hurricane landfalls in northeastern United States and Puerto Rico.
In a conceptual model of sand layer deposition in a backbarrier pond, it has been postulated that the stronger the hurricane, the greater the storm surge level and wave amplitude, and thus the more severe the overwash impacts and the more extensive the overwash fan [Liu and Fearn, 2000]. While this general principle has been supported by field evidence and core data based on recent or historical hurricanes [Donnelly and Webb, 2004], the physical mechanisms linking hurricane intensity, environmental forcing, and coastal overwash deposits have not been clearly elucidated. To better understand how overwash occurs and overwash deposits are laid down during extreme storm events, it is necessary to determine the character of the surge and waves as well as the flow conditions at the barrier and in the backbarrier pond. Collecting instrumental data of waves and currents at the barrier or backbarrier pond during a hurricane is infeasible, because of difficulties in predicting hurricane landfalls and placing delicate instruments in extreme conditions.

A modeling approach is the best way to estimate the environmental forcing during a hurricane landfall. This requires simultaneous simulation of physical processes that include surface winds and pressure, storm surge, astronomical tides, swell and seas, surf zone processes, and wave runup onto dry land. These processes, with different time and length scales, have been modeled separately with reasonable accuracy. Cheung et al. [2003] described a linkage of the processes to produce a forecast package for storm-induced coastal flooding. The package produces good agreement with measured winds, waves, and storm water levels as well as overwash debris lines on the south shore of Kauai, Hawaii for two recent hurricanes of known intensity and size. In addition to elucidating the environmental conditions associated with historical storms, the same modeling approach can be used to provide additional constraints in the interpretation of sedimentary data and estimate the storm parameters necessary to deposit prehistoric overwash sediments.

This paper examines the use of coastal overwash modeling to supplement sedimentary records in assessing hurricane intensity. The approach requires a suite of numerical models that compute coastal overwash at specific locations based on input storm tracks, central pressures, and radii of maximum wind. Previous paleotempestological studies have yielded sedimentary evidence of early historic and prehistoric hurricane landfalls in southern New England [Donnelly et al., 2001a]. The landfall of Hurricane Bob in 1991 provides a useful case study to validate the computed meteorological and oceanographic conditions. Comparison of computed overwash and field evidence allows assessment of the conceptual model of overwash layer deposition in backbarrier ponds and marshes and identifies key parameters that contribute to the deposition of these layers. The analysis produces modern analogs for the interpretation of geological proxy data from southern New England and sheds light on how coastal overwash modeling can be implemented in paleotempestology.

2. Coastal Overwash Modeling

The present study uses an updated version of Cheung et al. [2003] that provides a more complete account of the interactions among the various hydrodynamic processes during a hurricane event. The updated model package contains four components to simulate: (1) meteorological conditions, (2) astronomical tides and storm surge, (3) wave generation, propagation, and nearshore transformation, and (4) surf zone processes and runup onto dry land. The following sections provide a brief description of the four model components and their linkage and interoperability.

2.1. Meteorological Conditions

Accurate representation of hurricane wind and pressure, especially near the storm center, is a key to the entire simulation. A parametric model is most suitable for the proposed application, because it can provide the wind and pressure fields for early hurricane events, which at the most, only have track and intensity records. The present study considers the modified Rankine vortex model, which Phadke et al. [2003] and Tolman and Alves [2005] have shown to produce accurate hurricane wind fields for ocean wave modeling.

A parametric model of an idealized stationary hurricane represents the pressure and wind fields by concentric circles of isobars and isotachs. Schloemer [1954] proposed an exponential distribution of the pressure with distance r from the storm center as

\[
p = p_c + \Delta p \exp \left( -\frac{R_{max}}{r} \right)
\]

where \(p_c\) is the central pressure, \(R_{max}\) is the radius of maximum wind, and \(\Delta p\) is the pressure difference across the storm. The modified Rankine vortex model uses a shape parameter \(X\) to adjust the wind speed distribution in the radial direction

\[
V = V_{max} \left( \frac{r}{R_{max}} \right)^{\frac{X}{3}} \quad \text{for } r < R_{max}
\]

\[
V = V_{max} \left( \frac{R_{max}}{r} \right)^{\frac{X}{3}} \quad \text{for } r \geq R_{max}
\]

where \(V_{max}\) is the maximum wind speed. The value of \(X\) has been determined from observed hurricanes to have a range of 0.4 to 0.6 [Hughes, 1952]. Atkinson and Holliday [1977] studied numerous tropical cyclones in the northwest Pacific Ocean and constructed an empirical relationship for \(V_{max}\) in terms of the storm central pressure \(p_c\) as

\[
V_{max} = 3.44(1010 - p_c)^{0.644}
\]

where \(V_{max}\) and \(p_c\) have the units of m/s and mbar, respectively. Powell and Houston [1998] showed that this relation also gives accurate estimates for tropical cyclones in other basins.

The parametric wind field, which corresponds to mean boundary layer or gradient winds, is adjusted to the standard 10-m elevation using a correction factor of 0.8 [Powell and Black, 1990]. The resulting wind speed corresponds to sustained winds having an averaging time of 8 to
where $\beta$ is measured inward from the isobars. In the Northern Hemisphere, the forward motion of a hurricane increases the wind speed in the right quadrants and decreases the wind speed on the left. Jelesnianski [1966] suggested a correction to account for the asymmetric wind field:

$$
U(r) = \frac{R_{mw} r}{R_{mw} + r^2} V_F
$$

where $V_F$ is the storm forward velocity and $U$ is the correction term, which is vectorially added to the axisymmetric wind field from a parametric model. This relation, despite its intended application for slow moving hurricanes, has produced good results for fast moving hurricanes as well [e.g., Houston et al., 1999; Phadke et al., 2003].

### 2.2. Tides and Surge

[11] The Estuarine and Coastal Ocean Model (ECOM) of Blumberg [2002] is adapted to describe astronomical tides, storm surge, and wave setup. The variations of the water level $z$, flow depth $H$, and flow velocity $V = (U, V)$ over time $t$ are defined by a continuity equation and two momentum equations, which, in the Cartesian coordinates $(x, y)$, are given, respectively, by

$$\frac{\partial z}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = 0 \quad (6)$$

$$\frac{\partial U}{\partial t} + V \cdot \nabla U - fV = - \frac{\partial}{\partial x} \left( g \frac{z + p}{\rho_o} + F_x + \frac{\tau_x - \tau_{b_h}}{\rho_o H} \right) - \frac{1}{\rho_o H} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) \quad (7)$$

$$\frac{\partial V}{\partial t} + V \cdot \nabla V + fU = - \frac{\partial}{\partial y} \left( g \frac{z + p}{\rho_o} + F_y + \frac{\tau_y - \tau_{b_v}}{\rho_o H} \right) - \frac{1}{\rho_o H} \left( \frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right) \quad (8)$$

where $f$ is the Coriolis parameter; $g$ is acceleration due to gravity; $p$ is surface pressure; $\rho_o$ is water density; $(F_x, F_y)$ is horizontal diffusion; $(\tau_x, \tau_y)$ is surface shear stress; $(\tau_{b_h}, \tau_{b_v})$ is bottom shear stress; and $S_{xx}, S_{xy}$, and $S_{yy}$ are radiation stress terms derived from the wavefield.

### 2.3. Wave Generation and Transformation

[12] External forcing includes the surface wind shear stress and atmospheric pressure based on the hurricane model in section 2.1 as well as the tidal elevations on the ocean boundaries from the global tide model TPXO.6 [Egbert and Erofeeva, 2002]. The tides are provided as complex amplitudes of the Earth-relative sea surface elevation for eight primary ($M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1$) and two long-period ($M_e, M_n$) harmonic constituents on a 1440 x 721 global grid at 0.25° resolution. The governing equations are solved by a leapfrog finite difference technique with a staggered grid. The moving waterline is modeled through flooding and drying of the cells in response to water level changes at the cell interface.

[13] WA VEWATCH III (WW3) is a third-generation spectral wave model for wind wave development and propagation from deep to intermediate water [Tolman et al., 2002]. The action balance equation describes evolution of the wave spectrum $N$ and, when written in the latitude and longitude $(\xi, \psi)$ spherical coordinates, is given by

$$\frac{\partial N}{\partial t} + \frac{1}{\cos \xi} \frac{\partial}{\partial \xi} \left( N \cos \theta \right) + \frac{\partial}{\partial \psi} (\psi N) + \frac{\partial}{\partial \sigma} (k N) + \frac{\partial}{\partial \theta} (\theta N) = \frac{S}{\sigma} \quad (9)$$

where $\theta$ is direction, $k$ is wave number, $\sigma$ is intrinsic frequency, the overdot represents the rate of change, and $S$ includes energy input due to surface wind shear stress, quadratic nonlinear wave-wave interactions, and dissipation due to white capping and bottom friction. The equation is solved using a finite difference scheme with different time step sizes for time integration, spatial propagation, intraspectral propagation, and source term integration.

[14] Simulating Waves Nearshore (SWAN) is a third-generation, spectral wave model that describes the evolution of a wavefield under specified conditions of winds, currents, and bathymetry in shallow water [Booij et al., 1999; Ris et al., 1999]. The governing equation has a similar structure to that of WW3:

$$\frac{\partial N}{\partial t} + \frac{1}{\cos \xi} \frac{\partial}{\partial \xi} \left( N \cos \theta \right) + \frac{\partial}{\partial \psi} (\psi N) + \frac{\partial}{\partial \sigma} (\sigma N) + \frac{\partial}{\partial \theta} (\theta N) = \frac{S}{\sigma} \quad (10)$$

The term $S$ represents wind energy input, triad nonlinear wave-wave interaction, and dissipation due to white capping, bottom friction, and depth-induced wave breaking. The integration of the action balance equation is based on an implicit finite difference scheme in a Cartesian or spherical coordinate system with a constant time step for the propagation and source terms.

### 2.4. Surf Zone Processes and Runup

[15] Lynett et al. [2002] described a Boussinesq model for transformation of fully nonlinear and weakly dispersive waves in intermediate and shallow water. In contrast to the spectral wave models, this model provides a wave-by-wave description of the processes in the surf and swash zones. Let $h$ denote the free surface elevation and $\eta$ the water depth.
The depth-integrated governing equations in Cartesian coordinates are given as

\[
\eta_i + \nabla \cdot [(h + \varepsilon \eta)\mathbf{u}] - \mu^2 \nabla \cdot \left\{ \left( h + \varepsilon \eta \right) \left[ \frac{1}{6} \left( 2\eta^2 - \varepsilon \eta h + h^2 \right) \right] - \frac{1}{2} \frac{\partial}{\partial x_i} \left[ \nabla \cdot \mathbf{u} \right] + \frac{1}{2} \left( \varepsilon \eta - h \right) \nabla \left[ \nabla \cdot (h \mathbf{u}) \right] \right\} = O(\mu^4)
\]

(11)

\[
\mathbf{u}_i + \varepsilon \mathbf{u} \cdot \nabla \mathbf{u} + \nabla \eta + \mu^2 \left\{ \frac{1}{2} z_0 \nabla \nabla \cdot (h \mathbf{u}) + z_0 \nabla \nabla \cdot (h \mathbf{u}) \right\} + \varepsilon \mu^2 \left\{ \nabla \cdot (h \mathbf{u}) \right\} + \varepsilon \mu^2 \left\{ z_0 \nabla \left[ \nabla \cdot (h \mathbf{u}) \right] \right\} + \frac{\varepsilon}{2} \frac{\partial}{\partial x_i} \left[ \nabla \cdot \left( \nabla \cdot \mathbf{u} \right) \right] + \frac{\varepsilon^2}{2} \nabla \nabla \cdot (\nabla \cdot \mathbf{u}) + \delta_{ij} \left( \nabla \cdot \mathbf{u} \right) \nabla \cdot (h \mathbf{u}) + \eta \nabla \cdot (h \mathbf{u}) \mathbf{u} \right\}
\]

(12)

where \( \varepsilon \) and \( \mu \) account for the nonlinearity and frequency dispersion, \( \mathbf{R}_f \) and \( \mathbf{R}_b \) represent parameterization of bottom friction and wave breaking, and \( \mathbf{u} = (u, v) \) is evaluated at \( z_0 = -0.531h \) based on Nwogu [1993]. The numerical model utilizes a fourth-order predictor-corrector scheme and tracks the moving waterline in the swash zone by extrapolating the solution onto the beach.

The computational domain is analogous to a rectangular wave basin in a laboratory. The modeled coastline is located at one end of the basin and dissipative sponge layers are placed along the other three walls. Along a predefined line within the computational domain, waves are generated using a source function approach. The free surface elevation along the line source is given by

\[
\eta(x, y, t) = \sum_{i=1}^{M_x} \sum_{j=1}^{M_y} a_{ij} \sin \left[ k_i (x \cos \theta_j + y \sin \theta_j) - \sigma_i t + \phi_{ij} \right]
\]

(13)

where \( a_{ij} \) is the discrete spectrum from SWAN, \( \phi_{ij} \) is a random phase shift, and \( M_x \) and \( M_y \) denote the numbers of frequency and direction bins, respectively. The internal source generates the target waves through addition and subtraction of mass along the line source, emulating the excitation of a directional wave maker.

2.5. Model Linkage

[17] The model package runs on a PC-based Linux operating system. Figure 1 illustrates the modular structure of the model package. A set of Perl and shell scripts links the four model components with databases and utility programs, while a front-end preprocessor manages the data transfer and automates the simulation process. The package creates standardized input and output files that can be read and interpreted along the model execution path. Each simulation covers four levels of nested computational domains of increasing resolution: ocean, regional, coastal, and nearshore. Storm surge, astronomical tides, and waves are computed for the ocean, regional, and coastal domains, while surf zone processes and runup are computed in the nearshore domain. The Generic Mapping Tool (GMT) of Wessel and Smith [1991] interpolates user-supplied bathymetry and topography and generates the computational grids.

[18] The simulation covers the entire event of a hurricane as it traverses the ocean domain. The best track and radius of maximum wind define the pressure and wind fields through the hurricane model in section 2.1. The spectral wave model WW3 describes generation and propagation of hurricane waves in the ocean domain, while SWAN transforms the waves in the regional and coastal domains. ECOM calculates the astronomical tides and storm surge in the ocean domain and includes wave-induced currents and setup in the regional and coastal domains through the radiation stress from SWAN. The computed storm water level may in turn refine the SWAN calculation in the coastal domain. SWAN and ECOM output time series of wave spectrum and storm water level, respectively, at the offshore boundary of each nearshore domain, where the Bousinesq model continues the simulation into the surf and swash zones with greater accuracy.

3. Case Study

[19] Southern New England, which protrudes into the western Atlantic, lies in the paths of north tracking hurricanes. Although extreme events are relatively infrequent, sedimentary evidence and historical records show at least six intense hurricane landfalls over the last 700 years [Donnelly et al., 2001a]. The early events, for which track, size, and intensity are poorly known, are potential candidates for more detailed studies based on coastal overwash modeling. This will supply a more complete data set to estimate exceedance probabilities of extreme wind and coastal flood events in New England. Hurricane strikes of lesser intensity are relatively more frequent. Fourteen Category 1 and 2 hurricanes have made landfall in southern New England since 1851 [Landsea et al., 2004]. Hurricane Bob of 1991 is the most recent and has comprehensive meteorological, oceanographic, and overwash data to assess and
validate the proposed modeling approach and provide modern analogs for paleotempestological studies.

3.1. Storm Data

[20] Hurricane Bob of 1991 was the latest hurricane to make landfall in northeastern United States. The system, which originated from a frontal trough southeast of Bermuda, reached hurricane intensity 380 km east of Daytona Beach, Florida, at 1800 UTC on 17 August 1991. Figure 2 shows the best track of Hurricane Bob as it moved along the U.S. Atlantic coast. Houston et al. [1999] determined the radius of maximum wind of 38 km at 0250 UTC and 62.8 km at 1810 UTC on 19 August from surface and aircraft observations. A U.S. Air Force Reserves reconnaissance plane measured a wind speed of 61 m/s at the 700-mbar flight level at 0412 UTC on 19 August. A surface station recorded a pressure of 950 mbar at 0621 UTC on the same day when the hurricane was 165 km east-southeast of Norfolk, Virginia. The wind speed and pressure indicate a Saffir-Simpson category 3 hurricane. The storm weakened and expanded as it moved over cooler water off the mid-Atlantic coast. The eye passed over Block Island at 1720 UTC and made landfall at Newport, Rhode Island, around 1800 UTC on 19 August as a category 2 hurricane with a 14 m/s forward speed. Hurricane Bob crossed Rhode Island and Massachusetts and made the final landfall as a tropical storm near Rockland, Maine, at 0130 UTC on 20 August.

[21] The meteorological and oceanographic conditions were well recorded in the vicinity of New England during Hurricane Bob. Figure 2 shows the locations of three Coastal-Marine Automated Network (C-MAN) stations and four moored buoys operated by the National Data Buoy Center, and three water level stations operated by the Center for Operational Oceanographic Products and Service. Table 1 lists the station identifications, locations, water depths, and the anemometer elevations relative to mean sea level. Hourly records of wind speeds and directions were averaged over an 8-min period for the buoys and a 2-min period for the C-MAN and land stations. The algorithm of Liu et al. [1979] converts the recorded wind speed from their anemometer elevations to the standard 10-m elevation for comparison with model output. Water level stations take measurements at 6-min intervals with each measurement consisting of a set of 181 1-s water level samples. The buoys determine the significant wave height and mean and peak periods over a 20-min sampling period at 1-hour intervals.

[22] Thurm et al. [1991] provided a detailed account of the impact of Hurricane Bob along southern New England coasts. The storm caused $780 million of insured property damage and an estimated $1.5 billion of total loss in 1991 dollars. The surge and waves produced moderate to severe coastal flooding. Water was driven into the south facing Narragansett and Buzzards Bays and funneled up the smaller bays and coves. Aerial photographs showed numerous cottages were floated off their foundations and carried more than 100 m inland. Many boats were damaged and washed ashore. Storm water resulting from combined effects of the surge and waves reached 3.0 to 4.6 m above mean sea level at the head of Buzzards Bay. In Rhode Island, high-water marks between 3.1 and 5.0 m were recorded near Sakonnet Point. The high-water levels and storm waves caused beach erosion and in some cases breaching and overtopping of barriers.

3.2. Model Setup

[23] The case study provides hindcast estimates of storm water levels, wave conditions, and coastal overwash resulting from Hurricane Bob at five study sites in southern New England. The storm track and the locations of the study sites provide the necessary information to define the model domains and resolution. Figures 3 and 4 show the four

![Figure 2. Best track of Hurricane Bob and locations of nearby buoys, C-MAN stations, and tide gauges.](image)

Table 1. Meteorological and Oceanographic Measurements Near Hurricane Bob

<table>
<thead>
<tr>
<th>Station Type</th>
<th>Station</th>
<th>Latitude, °N</th>
<th>Longitude, °W</th>
<th>Distance to Storm, km</th>
<th>Water Depth, m</th>
<th>Anemometer Elevation, m</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISM1</td>
<td>C-man</td>
<td>43.78</td>
<td>68.86</td>
<td>54</td>
<td>-</td>
<td>32.7</td>
<td>Matinicus Rock, Maine</td>
</tr>
<tr>
<td>ISON3</td>
<td>C-man</td>
<td>42.97</td>
<td>70.62</td>
<td>19</td>
<td>-</td>
<td>32.3</td>
<td>Isle of Shoals, New Hampshire</td>
</tr>
<tr>
<td>44007 buoy</td>
<td>buoy</td>
<td>43.55</td>
<td>70.14</td>
<td>20</td>
<td>18.9</td>
<td>5.0</td>
<td>Portland, Maine</td>
</tr>
<tr>
<td>44013 buoy</td>
<td>buoy</td>
<td>42.35</td>
<td>70.69</td>
<td>14</td>
<td>55.0</td>
<td>5.0</td>
<td>Boston, Massachusetts</td>
</tr>
<tr>
<td>44008 buoy</td>
<td>buoy</td>
<td>40.50</td>
<td>69.43</td>
<td>238</td>
<td>62.5</td>
<td>5.0</td>
<td>Nantucket, Massachusetts</td>
</tr>
<tr>
<td>44025 buoy</td>
<td>buoy</td>
<td>40.25</td>
<td>73.17</td>
<td>101</td>
<td>36.3</td>
<td>5.0</td>
<td>Long Island, New York</td>
</tr>
<tr>
<td>BUZM3</td>
<td>C-man</td>
<td>41.40</td>
<td>71.03</td>
<td>34</td>
<td>-</td>
<td>24.8</td>
<td>Buzzards Bay, Massachusetts</td>
</tr>
<tr>
<td>8447930 water level</td>
<td>41.52</td>
<td>70.67</td>
<td>66</td>
<td>1.1</td>
<td>-</td>
<td>Woods Hole, Massachusetts</td>
<td></td>
</tr>
<tr>
<td>8452660 water level</td>
<td>41.51</td>
<td>71.33</td>
<td>3</td>
<td>1.1</td>
<td>-</td>
<td>Newport, Massachusetts</td>
<td></td>
</tr>
<tr>
<td>8455083 water level</td>
<td>41.36</td>
<td>71.49</td>
<td>0.5</td>
<td>-</td>
<td>Point Judith, Rhode Island</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
levels of nested computational domains with grid resolution ranging from 5 km to 4 m. The topography and bathymetry come from a wide variety of data sets, which have been converted to the WGS 84 datum and mean sea level for the generation of the computational grids.

Figure 3a shows the ocean domain, which extends into the western Atlantic Ocean with 30 (5 km) resolution. The large ocean surface to the south of New England allows sufficient time and fetch for the development of storm surge and waves through the numerical simulation. The General Bathymetric Chart of the Oceans compiled by British Oceanographic Data Centre in 2003 provides the bathymetry at 1° resolution. The regional domain in Figure 3b covers the continental shelf off New England. It has a resolution of 30 (900 m) for the transition between the 5 km ocean domain and the 9 (270 m) coastal domain as

Figure 3. Computational domain: (a) ocean, (b) regional, and (c) coastal.
shown in Figure 3c. The coastal domain extends sufficiently offshore to avoid high surge levels at the open boundaries that may adversely influence the calculation with ECOM. The Coastal Relief Model with $3''$ ($\sim 90$ m) resolution from National Geophysical Data Center defines the bathymetry and topography over the regional and coastal domains.

[25] The five study sites as shown in Figure 3c are Trustom Pond, Succotash Marsh, Briggs Pond, Quicksand Pond, and Homer Pond, which are located along the coasts.
of Rhode Island and Massachusetts near the hurricane landfall. Figure 4 shows the topography and bathymetry of the five nearshore domains at mean sea level. Each covers an area of about 3,500 m by 3,500 m with 4-m resolution. The U.S. Geological Survey Digital Elevation Model (DEM) with 10-m resolution defines the topography, while the Coastal Relief Model with 300 m resolution provides the bathymetry at the five sites. Narrow strips of coastal topography at Briggs Pond and Quicksand Pond are replaced by the NOAA LiDAR (Light Detection and Ranging) data taken in 2000 with 2-m resolution. These areas can be seen in Figures 4c and 4d with more detailed relief features. The low and sparse dune vegetation should have minimal effects on the LiDAR data at the barriers.

4. Model Validation

[26] The track, central pressure, and radius of maximum wind of Hurricane Bob and the tidal forcing at the ocean boundary during the event define the model input for the meteorological and oceanographic conditions. The wave and surge calculations are based on the predefined drag coefficients in WW3, SWAN, and ECOM. The actual drag coefficient, however, might be lower for very high surface wind speeds in the most intense hurricanes [Powell et al., 2003]. The storm passed over several C-MAN stations, buoys, and tide gauges around the time of its landfall. The measurements provide a valuable data set across the core of the storm for assessment and validation of the computed winds, pressure, astronomical tides, storm surge, and waves.

4.1. Winds and Pressure

[27] The wind speed and pressure distributions, as well as their peak values, are important for the storm surge and wave calculations. Instead of fine tuning the modified Rankine vortex model with the recorded winds from Hurricane Bob, an average shape factor of $X = 0.5$ is used to demonstrate the model’s capability in hindcasting wind fields for paleotempestological studies. The storm central pressure and location are interpolated from the best track values at 6-hour intervals. On the basis of the data from Houston et al. [1999], the radius of maximum wind is assumed to be 38 km below 35.6°N and 62.8 km above 41.4°N and is linearly interpolated between these two latitudes. Figure 5 provides comparisons of computed and measured wind speeds, wind directions, and surface pressure at four stations. BUZM3 is located just south of Buzzards Bay, Massachusetts; 44013, MISM1, and IOSN2 are further north along the hurricane track as shown in Figure 2.
These were selected because of their proximity to the track and the recorded winds and pressure in the core of the hurricane. Their closest distance to the track ranges from 14 km at BUZM3 to 54 km at MISM1 and is within the radius of maximum wind of 62.8 km around the time of landfall.

The comparisons show very good agreement between the computed and measured winds in the core of the storm. Both sets of data show almost the same wind speed and rapid direction change, when the hurricane crossed the stations. Away from the core at BUZM3, 44012, and MISM1, the computed winds are typically higher than the measurements. These stations are located along the coast, where the weaker winds in the periphery of the hurricane might be further reduced by the landmass. In addition, the measured winds exhibit some perturbations away from the core. These are most likely due to the rainbands around the hurricane that are not reproduced by the parametric model. As demonstrated by Phadke et al. [2003], hurricane waves are primarily generated in the zone of maximum wind to the right of the storm center. Wind field variations outside 3 to 4 of maximum wind to the right of the storm. Both sets of data show almost the same wind speed and rapid direction change, when the hurricane crossed the stations. Away from the core at BUZM3, 44012, and MISM1, the computed winds are typically higher than the measurements. These stations are located along the coast, where the weaker winds in the periphery of the hurricane might be further reduced by the landmass.

4.2. Storm Water Level

With still-water initial conditions, ECOM ran for 3.75 days to fully develop the astronomical tides in the ocean domain prior to the introduction of the hurricane at 1800 UTC on 18 August 1991. Figure 6a shows the computed water level at the maximum pressure drop of 950 mbar. The water level variation due to the storm and astronomical tides is clearly depicted in Figure 6a, except for the Bay of Fundy, where the color scale cannot resolve the 14-m tide range. The storm surge in the open ocean is a dome of water, known as the barometric tide, responding to the low pressure near the storm center. The maximum water level is only 0.7 m including the astronomical tides. The surge and tides interact nonlinearly resulting in undulation of the water level along the coast. Figure 6b shows the storm water level as Hurricane Bob made landfall. Onshore winds combined with shoaling of the surge cause a sharp increase of the water level to 1.6 m at the southern New England coast. Reductions of the coastal water level due to offshore winds on the left side of the storm are evident in both Figures 6a and 6b.

Figure 7 shows the maximum storm water level in the coastal domain during the storm event. The surge at the offshore boundary is around 1.1 m. The higher-resolution computation shows shoaling of the surge to around 1.7 m at the coasts and further increase in water level as the storm water funnels through inlets and bays. The computed water level at the head of Buzzards Bay is over 3.0 m and corroborates with the survey of Thurm et al. [1991]. Figure 8 shows the time histories of the recorded and computed storm water levels at the Woods Hole, Newport, and Point Judith tide gauges. These tide gauges are located in harbor basins, where the coastal domain with 270-m resolution does not fully represent the local conditions. The computed and recorded astronomical tides prior to the arrival of the surge show very good agreement at Newport and Point Judith, but some minor discrepancies at Woods Hole, which is located at the confluence of the tidal flows from the mid-Atlantic U.S. coast and the Bay of Fundy. The model tends to overestimate the tidal cycle with higher peaks and lower troughs at this location. The computed water levels at landfall agree reasonably well with the records at all three gauges thereby validating the storm surge calculation.

4.3. Storm Waves

The wave conditions of Hurricane Bob are simulated for a 2-day period starting 1800 UTC on 18 August 1991, when the storm center crossed into the ocean domain from the south. With the ambient weather pattern omitted, the modified Rankine vortex model along with its adjustments for elevation, inflow direction, and forward speed provides the hurricane wind forcing over the entire domain. Figure 9a shows the simulated wavefield of Hurricane Bob at its maximum pressure drop of 950 mbar. The category 3 hurricane had a radius of maximum wind of 42.9 km and a forward speed of 10.3 m/s. The results show a maximum significant wave height of 16.7 m to the right of the storm center, where the storm forward motion adds to the counterclockwise cyclonic wind flow. The radius of maximum wind increases to 62.8 km and the forward speed to 14.4 m/s as the storm moves north. The hurricane was downgraded to category 2 at 38.8°N prior to landfall because of the increase of the central pressure to 964 mbar. However, Figure 9b shows the larger storm and the increased forward speed generate a higher significant wave height of 17.8 m at landfall. The Saffir-Simpson scale is a good indication of the wind speed, but might not directly relate to the wave conditions, where other factors apply.

Figure 10 compares the computed wave conditions in the ocean domain with measurements. The computed wave height shows very good agreement at Buoy 44008 on the right side of the storm in the open ocean. The computed average wave period indicates strong correlation with the wave height and good agreement with the measured data. The model gives higher wave heights and longer periods at Buoy 44013 off Boston because it does not consider reduction of the wind speed as the storm crossed Rhode Island and Massachusetts. The model slightly overestimates the wave conditions at Buoys 44007 and 44025 on the left side of the storm. When Hurricane Bob moved along the U.S. east coast, the trajectories of the surface flow on the left side of the storm were primarily over land. The landward boundary layer friction likely weakened the wind field and subsequently the wavefield on the coastal side of the storm. The forward speed correction to the parametric model cannot account for the increased asymmetry due to land effects, but nevertheless, produces accurate results in relatively open ocean. Both the computed and measured peak periods show considerable scatter, as the wavefield under a hurricane is multimodal with frequency groups associated with seas and swell.
The storm wave conditions vary along the southern New England coast. Figure 11 shows the computed maximum wave height in the coastal domain during the storm event. While the storm water level is highest near the storm center from Narragansett Bay to Buzzards Bay, the largest waves occur to the east of Martha’s Vineyard. The five study sites experience increasing wave height from west to east, while the offshore wave direction varies from south southeast to south southwest. The results also show shadowing of the wave energy in sheltered areas and significant reduction of the wave height near the coastline due to breaking and white capping as well as other dissipation mechanisms over the shallow waters.

5. Overwash Modeling and Field Evidence

The computed storm water level for overwash modeling includes astronomical tides and storm surge at the offshore boundary of each nearshore domain. The Boussinesq model continues the simulation into the surf and swash zone wave

\[33\] The storm wave conditions vary along the southern New England coast. Figure 11 shows the computed maximum wave height in the coastal domain during the storm event. While the storm water level is highest near the storm center from Narragansett Bay to Buzzards Bay, the largest waves occur to the east of Martha’s Vineyard. The five study sites experience increasing wave height from west to east, while the offshore wave direction varies from south southeast to south southwest. The results also show shadowing of the wave energy in sheltered areas and significant reduction of the wave height near the coastline due to breaking and white capping as well as other dissipation mechanisms over the shallow waters.

5. Overwash Modeling and Field Evidence

The computed storm water level for overwash modeling includes astronomical tides and storm surge at the offshore boundary of each nearshore domain. The Boussinesq model continues the simulation into the surf and swash zone wave.

\[34\] The computed storm water level for overwash modeling includes astronomical tides and storm surge at the offshore boundary of each nearshore domain. The Boussinesq model continues the simulation into the surf and swash zone wave.
by wave. The computation is performed for 12 to 14 min, during which a quasi-steady-state condition is generated for the prescribed spectral wave conditions. The model outputs the flow depth in the domain and overtopping is indicated by flows over a barrier into the backbarrier pond. Table 2 summarizes series of simulations at the five sites around the time of landfall to estimate of the periods when overtopping of the barriers occurred. The storm water level and significant wave height are defined at the offshore boundary of the nearshore domains. Because of the storm forward motion, peak wave conditions occur slightly ahead of the peak storm water on the left side of the storm and vice versa on the right. The simulations at each site were computed for the peak storm water level and the peak wave height, and at selected times before and after these two peak conditions if overtopping occurs. Sediment transport can be significant under hurricane conditions. Dune erosion can modify the topography after a few episodes of overtopping, but would have little role in determining the overtopping threshold. The numerical results indicate the likely locations and durations of overtopping at each site for comparison with available field evidence of overwash and overwash deposits.

5.1. Trustom and Cards Ponds, Rhode Island

Trustom and Cards Ponds are located in South Kingstown at the southern coast of Rhode Island. Figure 4a shows the topography and bathymetry in the nearshore region. The ponds are actually coastal lagoons with an average depth of 0.4 m and are protected from the ocean by a narrow strip of dunes and beaches. The barriers are about 3 m high from mean sea level and have a couple of low spots, where previous inlets to the ponds existed. The tides do not affect the water level at Trustom Pond, except when breached by storms. Cards Pond receives a significant supply of water from Moonstone Stream and is intermittently open to the sea through breaching of an ephemeral inlet. The coast is lined with mixed sand and gravel beaches, sandy beaches, and rocky outcrops. The subtidal zone consists of both sandy bottom and hard-bottom glacial deposits with gravel and boulders. The nearshore seabed contours are generally straight and parallel to the coastline with a relatively steep slope of 0.15.

The simulation results summarized in Table 2 indicate the surge and waves overtopped the low-lying, relic inlet areas for about 4 hours and caused minor, intermittent overtopping of the 3-m-high barrier for about an hour under...
the peak surge condition. Figure 12a shows the wavefield at 1810 UTC, when the storm made landfall and the storm water level peaked at 1.41 m at the site. The wavefield shows a system of well-defined swell approaching the barriers from the south southeast and a component of seas generated locally by the hurricane winds from the east southeast. Despite the wide breaches at the inlet areas, the waves in the ponds have limited amplitudes because of the shallow water. Figure 12b shows the wavefield at 2020 UTC, when the storm center was 110 km north of the site. The results indicate typical choppy waves at the rear of a hurricane as well as small-amplitude seas generated locally by the hurricane winds from the west southwest. With a smaller wave height and a lower storm water level, the model shows intermittent overtopping at the inlets only.

The numerical results are evaluated against the aerial photographs in Figure 13 taken before and after Hurricane Bob. The vegetation and sandy areas as well as backbarrier
subaqueous sediment deposits are clearly discernable in the back-and-white photographs. The positions of the relic inlets to the ponds are marked by 1 and 2 in the photographs. Between 1988 and 1992, an overwash fan formed behind the inlet to Trustom Pond and the bare sand dune adjacent to the Cards Pond inlet extended further west and north. The dune vegetation along the barrier became irregular and discontinuous at locations marked by 3 and 4 in the

Figure 10. Comparison of computed and measured wave conditions at buoys. Circles indicate measurement; curves indicate WW3.

Figure 11. Computed maximum wave height of Hurricane Bob at southern New England coast. Curve shows storm track.
The erosion of the dune vegetation occurred during this period is consistent with minor damage to topsoil and root systems by intermittent wave overtopping. However, there is no field evidence of overwash deposits behind the dune ridge. The damage to the dune vegetation was completely recovered and the bare sand dune next to the Cards Pond inlet was covered by vegetation by 2001.

As other storm events occurred between 1988 and 1992, the aerial photographs in Figure 13 do not provide definitive evidence that Hurricane Bob caused the dune erosion and overwash fans. Additional data and analysis are necessary. Though Hurricane Bob was the only hurricane that made landfall on the New England coast from 1988 to 1992, there were numerous extratropical storms in the area during the same period. The Halloween storm in October 1991 immediately following Hurricane Bob is the most notable. However, the tide gauge data at nearby Woods Hole and Newport from 1988 to 1992 shows that Hurricane Bob caused the highest water levels at 1.80 and 1.78 m,

### Table 2. Overwash Simulations Around the Time of Hurricane Landfall

<table>
<thead>
<tr>
<th>Test Run</th>
<th>Simulation Start Time, UTC</th>
<th>Storm Water Level, m mean sea level</th>
<th>Significant Wave Height, m</th>
<th>Overtopping</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trustom Pond, Rhode Island</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1700</td>
<td>0.58</td>
<td>3.32</td>
<td>inlet</td>
</tr>
<tr>
<td>2</td>
<td>1810</td>
<td>1.41</td>
<td>3.25</td>
<td>inlet/barrier</td>
</tr>
<tr>
<td>3</td>
<td>1920</td>
<td>0.71</td>
<td>3.08</td>
<td>inlet/barrier</td>
</tr>
<tr>
<td>4</td>
<td>2020</td>
<td>0.51</td>
<td>2.72</td>
<td>inlet</td>
</tr>
<tr>
<td>5</td>
<td>2100</td>
<td>0.42</td>
<td>2.55</td>
<td>inlet</td>
</tr>
<tr>
<td>6</td>
<td>2200</td>
<td>0.22</td>
<td>2.15</td>
<td>-</td>
</tr>
<tr>
<td><strong>Succotash Marsh, Rhode Island</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1710</td>
<td>1.04</td>
<td>4.68</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1800</td>
<td>1.42</td>
<td>4.41</td>
<td>-</td>
</tr>
<tr>
<td><strong>Briggs Pond, Rhode Island</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1620</td>
<td>0.45</td>
<td>4.21</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1820</td>
<td>1.64</td>
<td>5.64</td>
<td>inlet/barrier</td>
</tr>
<tr>
<td>3</td>
<td>1920</td>
<td>1.12</td>
<td>5.45</td>
<td>inlet/barrier</td>
</tr>
<tr>
<td>4</td>
<td>2110</td>
<td>0.47</td>
<td>3.85</td>
<td>-</td>
</tr>
<tr>
<td><strong>Quicksand Pond, Rhode Island</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1630</td>
<td>0.51</td>
<td>4.16</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1720</td>
<td>1.07</td>
<td>5.26</td>
<td>inlet</td>
</tr>
<tr>
<td>3</td>
<td>1820</td>
<td>1.66</td>
<td>5.46</td>
<td>inlet</td>
</tr>
<tr>
<td>4</td>
<td>1940</td>
<td>0.95</td>
<td>5.38</td>
<td>inlet</td>
</tr>
<tr>
<td>5</td>
<td>2040</td>
<td>0.68</td>
<td>4.76</td>
<td>-</td>
</tr>
<tr>
<td><strong>Homer Pond, Massachusetts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1710</td>
<td>0.79</td>
<td>5.87</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1750</td>
<td>1.23</td>
<td>6.32</td>
<td>low spot</td>
</tr>
<tr>
<td>3</td>
<td>1830</td>
<td>1.45</td>
<td>6.48</td>
<td>low spot</td>
</tr>
<tr>
<td>4</td>
<td>1910</td>
<td>1.24</td>
<td>6.50</td>
<td>low spot</td>
</tr>
<tr>
<td>5</td>
<td>1940</td>
<td>0.96</td>
<td>6.46</td>
<td>low spot</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>0.79</td>
<td>6.40</td>
<td>-</td>
</tr>
</tbody>
</table>

![Figure 12](image_url)  
**Figure 12.** Computed wavefields near Trustom and Cards ponds. (a) Peak storm water at 1810 UTC. (b) Rear of hurricane at 2020 UTC.
while the Halloween storm produced the second highest at 1.22 and 1.63 m, respectively. Buoy 44008 located off the study site recorded a maximum significant wave height of 11.4 m during Hurricane Bob in comparison to 9.6 m during the Halloween storm. These all indicate that Hurricane Bob caused more severe storm water and wave conditions than the Halloween storm at the study site.

39 The 2001 aerial photograph shows increased dune vegetation coverage, but no increase in the size of the overwash fans from 1992 to 2001, despite the occurrence of severe extratropical storms in January 1996, November 1997, January 1997, and January 1998. The lack of any geomorphic change associated with these events points to the relatively minor impacts of the extratropical storms in the area and singles out Hurricane Bob as the most likely among the events that caused the dune erosion and overwash fans at the study site between 1988 and 1992. The south facing orientation of this and the other four sites make them much more susceptible to landfalling hurricanes with intense southerly winds than to oceanic winter storms, which generally have strong northeast winds [Donnelly et al., 2001a; 2001b; Donnelly and Webb, 2004].

5.2. Potter’s Pond and Succotash Marsh, Rhode Island

40 Potter’s Pond and Succotash Marsh are a salt pond and a backbarrier salt marsh, respectively. Figure 4b shows the topography and bathymetry of the site, which is located at East Matunuck, Rhode Island, about 3.2 km east of Cards Pond. The barrier-marsh-pond complex overlies glacial till and outwash deposits south of the recessional Charlestown Moraine with glacial till occasionally exposed at the surface as small islands. The barrier beach is a result of the west-to-east littoral drift and most of the sediment comes from the erosion of glacial deposits at Matunuck Point less than 2 km to the west [McMaster, 1960]. The present beach height is approximately 3 m above mean sea level and is similar to the 2.5- to 3-m height measured by Simpson [1977].

41 Two salt ponds separate Succotash Marsh from the mainland. Potter’s Pond is located to the northwest and Point Judith Pond to the northeast. The tide range on the ocean side of the barrier is approximately 1 m, with extreme spring tides reaching 1.5 m. Tidal exchange occurs only through the Point Judith Breachway to the east of Succotash Marsh. The breachway was excavated in 1909 and three breakwaters that form the Point Judith Harbor of Refuge were completed in 1914. Prior to the construction of the breachway, Potter’s and Point Judith Ponds were connected to the ocean via the currently abandoned channel network within Succotash Marsh [Donnelly et al., 2001a]. The relic channels that terminate at the modern barrier are evidence indicating the positions of past inlets likely created by storms. In fact, the Great September Gale of 1815 opened this old inlet, which remained active until sealed by longshore sediment shortly after 1903.

42 Donnelly et al. [2001a] documented six large-scale overwash fans deposited in Succotash Marsh since about 1300 A.D., but none attributable to Hurricane Bob. The 1988 and 1992 aerial photographs in Figure 14 show intact dune ridges before and after Hurricane Bob confirming that the dunes fronting Succotash Marsh and Potter’s Pond were not overtopped or breached during the storm. A comparison of the aerial photographs reveals that approximately 20 m of erosion of the seaward dune in front of Succotash Marsh occurred during that interval. A small-scale overwash fan extends 10 to 20 m beyond Succotash Road at the far eastern margin of the study site as shown in the 1992 photograph. The barrier fronting Potter’s Pond also appears to have been eroded and most of the dune vegetation was removed between 1988 and 1992. The unvegetated sand extends back nearly to the marsh fringing the south shore of Potter’s Pond. The only overtopping at the site occurred at the barrier fronting Matunuck Point Pond (indicated by MPP in the 1992 photograph). The observed erosion is most likely due to Hurricane Bob, which was the most severe storm at the site between 1988 and 1992.

43 Table 2 summarizes the model runs at the peak surge and peak wave conditions during Hurricane Bob. The
corresponding wavefields in Figure 15 corroborate the findings from the field studies and aerial photographs. The computed results show overtopping only of the low-lying barrier at Matunuck Point Pond. The surge and waves are not sufficient to overtop the barrier beach fronting Potter’s Pond and Succotash Marsh. This may appear to contradict the model results at Trustom and Cards Ponds. The wave height increases toward the east from Trustom Pond, while the barrier elevation is similar at Succotash Marsh. An examination of the bathymetry and wave patterns reveals that the seabed in front of Trustom Pond is steeper and larger waves can reach closer to the beach. The

Figure 14. Aerial photographs of Succotash Marsh and Potter’s Pond in 1988 and 1992.

Figure 15. Computed wavefields near Succotash Marsh and Potter’s Pond. (a) Peak wave height at 1710 UTC. (b) Peak storm water at 1800 UTC on 19 August 1991.
The seabed slope in front of Succotash Marsh is much smaller and the shallow nearshore region limits the wave height at the beach. In addition, the concave seabed in front of Succotash Marsh refracts the waves to the west and east, further reducing the wave height at the beach and the likelihood of barrier overtopping.

### 5.3. Briggs and Quicksand Ponds, Rhode Island

Briggs and Quicksand Ponds are located adjacent to each other in Little Compton, Rhode Island, along the south facing Atlantic shoreline near Buzzards Bay. Quicksand Pond is 4 km to the northeast of Briggs Pond and is the larger of the two with an area of 1.6 km$^2$. Briggs Pond covers nearly half the area of Quicksand Pond at 0.75 km$^2$. The topography and bathymetry at the two sites are shown in Figures 4c and 4d. The two ponds are relatively shallow embayment around 2 to 3 m deep and are separated from the open ocean by narrow barrier beaches composed mainly of sand and sparse gravel. Dune ridges run parallel to the shoreline at an average height of 2 to 3 m above mean sea level and supratidal grasses and shrubbery extend beyond the dunes to the backbarrier vegetation. Each pond currently has a tidal inlet with a well-developed flood tidal delta. Analysis of historical aerial photographs and charts reveals that the inlet locations have remained relatively stable since at least 1860 [FitzGerald, 1993].

Briggs and Quicksand Ponds are situated 10 km east of Newport, Rhode Island, where Hurricane Bob made landfall in 1991. The proximity of these ponds to the hurricane and their positions on the right side of the track indicate that these ponds likely experienced severe onshore winds, waves, and surge conditions. Table 2 summarizes the series of simulations performed for these two sites. The computed peak storm water levels are about 1.65 m and the peak significant wave heights are 5.64 and 5.46 m at the offshore boundaries of the Briggs Pond and Quicksand Pond domains, respectively. The computation shows that storm water overtopped the inlet and barrier at Briggs Pond for about 1 hour and the inlet at Quicksand Pond for about 2 hours. Figure 16 shows the numerical results at the two sites under the peak storm water conditions. At Briggs Pond, the model suggests that the barrier was overtopped near the inlet and along a larger section to the east. The results for Quicksand Pond show barrier breaching only in the area surrounding the tidal inlet and limited wave activities in the central part of the pond. The flow conditions had the potential to deposit small-scale overwash fans behind the dune ridge of both ponds.

Figures 17 and 18 show aerial photographs taken before and after Hurricane Bob at Briggs and Quicksand Ponds, respectively. While the width of the barrier beach and backbarrier marsh remained fairly stable during this period, the extent of exposed sandy area versus vegetated area changed significantly at both locations. In 1988, the barrier and backbarrier systems were covered by dune and marsh vegetation as can be seen by the dark gray color behind the dune ridge in the aerial photographs. The 1992 photographs, which were taken during the winter, show ice coverage immediately behind the barriers as well as large sections of exposed sand around the inlets and along the barriers. The change in the extent of exposed sandy areas and the fan-like shape of these sandy regions in the 1992 aerial photographs are consistent with the locations of overtopping as indicated by the numerical model results in Figure 16. The reinvigoration of the tidal inlets at Quicksand and Briggs Ponds between 1988 and 1992 is likely due to Hurricane Bob and is consistent with impacts from past hurricane strikes.

The model results and aerial photographs of Briggs Pond indicate that moderate overtopping occurred in the western region of the barrier near the tidal inlet. The flood tidal delta enlarged in conjunction with the reinvigoration of the inlet between 1988 and 1992. The barrier beach immediately to the east of the knob was breached and a fan-shaped area of exposed sand is present in the 1992 photograph. Storm waves and surge widened the barrier at this location by overtopping and eroding the dune and depositing sediment into the pond. Further east, the beach area was widened while the dune ridge vegetation became thinner and discontinuous in 1992. At Quicksand Pond, the model results and aerial photographs show overtopping occurred mainly in the central section of the barrier near the tidal inlet. Backbarrier subaqueous sediment is visible in the 1992 photograph, suggesting the deposition of flood tidal

---

**Figure 16.** Computed wavefields at peak storm water at 1820 UTC on 19 August 1991: (a) Briggs Pond and (b) Quicksand Pond.
delta sediments over that time period, though differences in turbidity and light conditions may impact the visibility of subaqueous features in the aerial photograph. Modest overwash occurred in the western section of the barrier, covering barrier vegetation behind the dune ridge but not penetrating into the backbarrier pond. The eastern section of the barrier at Quicksand pond shows little evidence of overwash occurring during this time period.

Several cores taken from the central region of Quicksand Pond north of the flood tidal delta do not record sedimentary evidence attributable to Hurricane Bob, but contain evidence of numerous earlier historic and prehistoric storm-induced layers dating back 5000 years. The lack of a sedimentary signal from Hurricane Bob in the center of Quicksand Pond is not surprising given the distance from the barrier at several hundred meters, and the relatively minor barrier overtopping and small waves in the pond observed in the numerical model results. Short (<1 m) push cores were collected from Quicksand Pond behind the central section of the dune ridge and along the southern shore of the pond. A 20- to 40-cm-thick layer of sand overlying a thin (~1 cm) layer of peat is contained near the top of the cores, providing evidence of recent deposition of sand. This sand layer may have been laid down in the flood tidal delta, when storm water surged through the inlet during Hurricane Bob. Although this may provide field data in support of the model results, additional work is necessary to determine the age and extent of this deposit before it can be confidently attributed to Hurricane Bob.

5.4. Long Cove and Homer Pond, Massachusetts

Long Cove and Homer Pond are two of a series of elongated, back-barrier ponds situated along the south coast of Martha’s Vineyard near Cape Cod, Massachusetts. Figure 4e shows the topography and bathymetry of the study area. Homer Pond is 900 m long and 200 m wide, and has water depths of 2 to 3 m. Long Cove situated to the west...
has approximately twice the dimensions of Homer Pond and water depths of 3 to 4 m. Both are separated from the ocean by a 125-m-wide barrier beach. A well-developed dune ridge rises up to about 3 m above mean sea level, except at a couple of low spots that might have been eroded by storm waves or served as inlets to the ponds. The dune and beach are mainly composed of well-sorted coarse sand. The coastline in the area is relatively straight with an average nearshore slope of 0.02 from the waterline down to the 9-m depth contour.

[50] The study area is located about 60 km east of Newport, Rhode Island, where Hurricane Bob made landfall. Given the radius of maximum wind of 62.8 km and the storm asymmetry due to its forward motion, this location was subject to the most severe wind and wave conditions among the sites considered in this study. Table 2 indicates the combinations of surge and wave conditions capable of overtopping the low spots of the barrier fronting Homer Pond during a 2-hour period. The computed peak storm water level is 1.45 m, while the corresponding significant wave height at the offshore boundary of the computational domain is around 6.5 m. The computed wavefield as shown in Figure 19 indicates a well-defined system of swell as well as a strong component of seas generated locally by the hurricane winds. A significant amount of wave energy propagates into Homer Pond and Long Cove as well as the adjacent Tisbury Great Pond through the low-lying sections at the barriers.

[51] Figure 20 shows the aerial photographs of the study area taken before and after Hurricane Bob. The March 1991 photograph shows dense vegetation along the dune ridge, except at a few low spots, before the storm. The 1992 photograph shows fresh overwash fans and erosion of dune vegetation at the barrier fronting Homer Pond and Long Cove. The surge and waves of Hurricane Bob most likely developed the overwash fans and caused the dune erosion as suggested by the numerical model results. A comparison between the 1991 and 1992 photographs shows significant erosion of the beach on the east shore of Tisbury Great Pond during this interval. Figure 19 shows the waves breaching the barrier propagate obliquely to this shore. The subsequent longshore current might have transported the beach sand into the deeper part of the pond to the north.
Figure 21 shows a picture of the overwash fan at Homer Pond taken during a field survey in 1999. The surge and waves of Hurricane Bob breached the barrier, resulting in a distinct gap in the dune ridge and the formation of an overwash fan extending into the pond. Sediment cores taken from the southern part of the pond contain a prominent sand layer at the top that could be attributed to the storm. This sand layer is about 24 cm thick in cores taken 35 m from the edge of the overwash fan and thins out toward the center of the pond, but it is still detectable in cores taken more than 100 m away from the fan. Backbarrier pond deposits like this one provide records of past hurricane strikes and represent the principal geological proxy data used in paleotemestological studies.

6. Implications in Paleotempestology

Many large-scale overwash deposits recovered from backbarrier ponds and marshes in northeastern United States have been attributed to intense hurricane landfalls [Donnelly et al., 2001a, 2001b, 2004a]. In particular, Donnelly et al. [2001a] documented six large-scale overwash fans deposited in Succotash Marsh since about 1300 A.D. Figure 22 shows a photograph of the sand layers separated by peat deposits (in darker color) between the storm events. The age of the four uppermost storm-induced layers matches the historical record of intense hurricane landfalls in southern New England. These fans were most likely deposited by intense hurricanes in 1954, 1938, 1815, and either 1638 or 1635. Radiocarbon dating of the lower two overwash fans indicated that these were deposited between 1295–1407 A.D. and 1404–1446 A.D. and probably represent prehistoric hurricane strikes. Recent core samples gathered from Quicksand Pond contain evidence of numerous early historic and prehistoric storm-induced layers dating back 5000 years. Further regional-scale studies from different depositional environments (i.e., marshes, lagoons, salt ponds, and fresh ponds) are currently underway to map the history of storm-induced coastal overwash. Developing good estimates of the intensity of past storm events from overwash deposits is essential. Numerical modeling can further the objectives of paleotempestology by providing modern analogs to interpret the geological proxy data and a systematic approach to reconstruct early historic and prehistoric hurricane landfalls.

6.1. Modern Analogs

As in any paleoscience field involving reconstruction of past patterns and processes, paleotempestology uses modern analogs derived from known hurricane events for the interpretation of geological proxy evidence. Field obser-
Observations on the impacts of a hurricane strike of known characteristics can provide evidence linking the sedimentary data with depositional mechanisms. Coastal overwash modeling provides a vital link between the depositional mechanisms and oceanographic conditions under specific sets of hurricane parameters. Model results from known or hypothetical hurricanes can also provide guidance in selecting sites for geological proxy studies.

This study provides insight into the oceanographic conditions during Hurricane Bob and the surge and wave conditions at the coastlines, where overwash occurs. The models describe the dynamic processes responsible for barrier overtopping and provide essential information regarding flow conditions at and behind the barriers for the interpretation of the pattern and extent of overwash deposits. The estimates of surge, waves, and barrier overtopping at the study sites provide a means of not only assessing the processes associated with Hurricane Bob, but can be used to provide constraints on the interpretation of early overwash deposits for which little or no instrumental data is available. For example, given the minimal amount of overtopping and low-amplitude waves in Quicksand Pond predicted by the model study for Hurricane Bob, it is likely that extensive overwash layers preserved within the pond were deposited by storms that were significantly more intense.

The differences in observed and simulated overwash between Trustom Pond and Succotash Marsh also provide useful information for paleotempestological work. The results suggest that even in adjacent sites overwash processes can differ resulting from relatively subtle differences in local bathymetry and geomorphology. In the case of Hurricane Bob, the steeper slope of the seabed at Trustom Pond relative to Succotash Marsh led to larger waves impacting the barrier at Trustom Pond. The seabed fronting Succotash Marsh has a more gentle slope causing the waves to break further offshore. Waves impacting the beach at Succotash Marsh were further reduced in height, relative to those at Trustom Pond, as a result of refraction over the concave seabed. These results indicate that Trustom Pond is more susceptible to overwash than Succotash Marsh despite their proximity and similar barrier heights. The six hurricanes causing overwash deposits in Succotash Marsh during the

![Figure 21. Overwash fan at Homer Pond in 1999.](image)

![Figure 22. Storm-induced sand overwash layers preserved in Succotash Marsh.](image)
last 700 years likely produced more severe surge and wave conditions than Hurricane Bob. Conversely, Trustom Pond may contain more overwash layers from less intense or more distant hurricane landfalls during the same period.

[57] This study is the first step in the realization of the full potential of coastal overwash modeling in paleotempestology. Modern analogs from more than one event are necessary. Model studies of hurricane landfalls of different intensities and locations will provide ranges of data to infer the characteristics of early historic and prehistoric hurricanes. Hurricane Carol of 1954 and the hurricane of 1938 were category 2 and 3 storms, respectively, when they made landfall on the Long Island coast. Both hurricanes have best track data and tide gauge measurements and produced overwash deposits in Succotash Marsh, Quicksand Pond, and numerous other locations. These two events will provide an interesting comparative study, because Hurricane Carol was a minimal category 2 storm at landfall, but produced nearly as much surge as the strong category 3 hurricane in 1938. Numerical modeling of the these two hurricanes along with the results from Hurricane Bob in this study will provide a useful set of modern analogs for paleotempestological studies of New England hurricane landfalls. The intense hurricanes in 1869, 1821, 1815, and 1635 that resulted in significant overtopping and breaching of the barriers along the southern New England coast would be good candidates for further investigation.

6.2. Reconstruction of Early Hurricanes

[58] Reconstruction of early historic and prehistoric hurricanes is an order of magnitude more complex compared to the modern analog approach and requires geological proxy data at multiple locations to account for the uncertainties in storm characteristics and paleotopography. While early maps and navigational charts may provide a reference for the topography and bathymetry at the study sites, the long-term trends of land and sea levels are available from proxy and instrumental data sets [e.g., Emery and Aubrey, 1991; Donnelly et al., 2004b]. The models can qualitatively hindcast whether overwash and overtopping of the barriers occurred or not. By altering the storm central pressure, radius of maximum wind, forward speed, and track as well as the tide level and barrier height in a simulation, the output can be compared with the proxy evidence to infer the characteristics of the hurricane strike. This multivariate inverse analysis involves a large parameter space, which must be reduced, and additional constraints must be identified, to make the method feasible.

[59] The hurricane model described in section 2.1 provides an approximation of the pressure and wind fields through the central pressure, radius of maximum wind, and forward speed. Although these storm parameters vary along the track, the timescale of their variation is large compared to those of wave and surge generation within the storm. The model may use a single set of parameters at the time of landfall throughout the entire simulation. This is consistent with the Standard Project Hurricane approach recommended by the National Weather Service and U.S. Army Corps of Engineers for hurricane impact assessment [Schwerdt et al., 1979]. An analysis of the HURDAT database compiled by Landsea et al. [2004] shows that most of the hurricanes making landfall in southern New England approached from the south southwest parallel to the mid-Atlantic U.S. coast. These events originated in the deep tropics south of 25°N and traveled north or northwest toward the U.S. east coast before recurving around the western edge of the subtropical ridge, known as Bermuda High, toward northeastern United States. This suggests paleohurricanes making landfalls in southern New England would have followed the same climatological pattern and could be modeled using a generic track that runs parallel to the mid-Atlantic U.S. coast and varies with landfall location only.

[60] Of the three storm parameters, the central pressure is the primary parameter controlling the storm intensity. The wind field, storm surge, and wave conditions also depend on the radius of maximum wind and forward speed. An option to simplify the inverse analysis is to approximate the radius of maximum wind and forward speed using statistical relations derived from historical storm data. The radius of maximum wind may be given by

$$R_{mw} = \exp \left(2.636 - 0.0005086\Delta p^2 + 0.0394899\xi\right)$$  (14)

where the pressure drop $\Delta p$ is in mbar and the latitude $\xi$ in degree [Vickery et al., 2000]. The forward speed can be estimated from CLIPER (Climatology and Persistence) using storm categories and locations as input [Neumann, 1972; Aberson, 1998]. CLIPER is a multiple regression statistical model developed and used by National Weather Service for hurricane track forecasts. Both equation (14) and CLIPER, which are based on large numbers of Atlantic hurricanes from the HURDAT database, reflect the climatology of hurricanes that move into cooler mid Atlantic waters off New England. At the two locations where the radius of maximum wind of Hurricane Bob was measured to be 38 and 62.8 km, equation (14) gives reasonable estimates of 46.5 and 62.4 km, respectively. CLIPER provides a forward speed estimate of 15 m/s at landfall as compared to the observed forward speed of 14 m/s. Deriving the radius of maximum wind and forward speed from statistical relationships could reduce the parameter space of the storm characteristics to just the central pressure and landfall location.

[61] The astronomical tides together with the storm surge increase the nearshore water depth and exacerbate the wave conditions at the coastline. The storm water level also determines whether or not a barrier is completely submerged and the subsequent wave energy dissipation and transmission. The overtopping events summarized in Table 2 are significantly shorter than the semidiurnal tidal cycle in the region. The astronomical tide level may be considered as constant in the inverse analysis. The barrier height is another important parameter that determines the overtopping threshold, and once overtopping occurs, it controls the wave energy that can be transmitted into the backbarrier pond. The effects of barrier height and water level on the overtopping threshold are complementary. Correlation of the overwash deposit patterns with the computed flow conditions at the barrier and in the backbarrier pond may provide an additional constraint in the inverse analysis. Potential misfits between model results and observed overtopping may point to the importance of coupling between surge and waves and geomorphological changes. By simply
varying the barrier height during the simulation, we can assess the sensitivity of the system to geomorphic changes that might be expected to occur throughout the course of the storm.

Using the numerical modeling approach, a series of simulations can be run to determine the combination of storm central pressure, landfall location, astronomical tide level, and barrier height that yields the flow conditions capable of producing the observed overwash deposits. With geological proxy data at multiple sites, it is possible to identify the stretch of coastline impacted by a hurricane and infer the landfall location prior to the inverse analysis. The analysis may in turn identify additional sites for geological proxy data to better constrain the central pressure and landfall location. This approach has the benefit of cross-checking the results at multiple sites along a gradient from close to the landfall location to more distant sites and will provide more confidence in the resulting inferences of the storm characteristics.

7. Conclusions

This paper has shown that coastal overwash modeling can be a useful tool in paleotempestology. Hurricane Bob, with its well-documented meteorological and oceanographic conditions and impacts along the New England coastlines, provides a very good test case for this endeavor. The computed winds, pressure, waves, and storm water levels give very good agreement with measured data near the track and on the right side of the hurricane, where coastal barriers are prone to overtopping. The computed overwash and overtopping conditions show strong correlation with aerial photos and field evidence at all five backbarrier sites in southern New England.

Though additional modern analogs from hurricanes of different sizes and intensities are necessary to augment the data presented in this study, the analysis of Hurricane Bob demonstrates that numerical modeling can describe the dynamic processes responsible for barrier overtopping and provide critical insights for interpreting the sedimentary record of storms in southern New England. The results provide a means of evaluating the susceptibility of different sites to overtopping and breaching for a given suite of storm parameters. This modern analog approach provides much needed constraints in deducing storm parameters from sedimentary records as well as guidance in selecting sites for geological proxy studies.

Regional-scale studies from different depositional environments are currently underway to map the history of storm-induced coastal overwash in northeastern United States. Numerical modeling provides a vital link between the storm characteristics and the flow conditions at the barriers that are capable of producing the observed overwash deposits. The geological proxy data at multiple locations will allow a multivariate inverse analysis of the storm central pressure, landfall location, astronomical tide level, and barrier height in deducing early historic or prehistoric hurricane events. This coupling of numerical modeling and geological proxy techniques offers a means of providing additional constraints on the uncertain paleo-pography and storm characteristics.

Acknowledgments. The Risk Prediction Initiative of the Bermuda Biological Station for Research, Inc. supported this study via grants to University of Hawaii, Woods Hole Oceanographic Institute, and Louisiana State University. The National Science Foundation provided additional funding support through grant EAR-0519118 to Woods Hole Oceanographic Institute and BCS-0213884 to Louisiana State University. The Office of Naval Research funded the development of the storm surge and wave modeling package through grant N00014-02-1-0903 and contract N00014-05-C-0392 to University of Hawaii. We would like to thank A. Brad Murray, Associate Editor, and the two anonymous reviewers for their thorough reviews and constructive remarks that have greatly improved this paper. This is SOEST contribution 7064 and BBSR contribution 1969.

References


K. F. Cheung, Department of Ocean and Resources Engineering, University of Hawaii at Manoa, Holmes Hall 402, Honolulu, HI 96822, USA.

J. P. Donnelly, Department of Geology and Geophysics, Woods Hole Oceanographic Institute, Woods Hole, MA 02543, USA.

S. H. Houston, Central Pacific Hurricane Center, National Weather Service, Honolulu, HI 96822, USA.

K.-B. Liu, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA.

X.-Z. Mao, Graduate School at Shenzhen, Tsinghua University, Shenzhen 518055, China.

R. J. Murnane, Risk Prediction Initiative, Bermuda Biological Station for Research, Inc., St. George’s GE01, Bermuda.

E. M. Scileppi, Department of Geological Sciences, Brown University, Providence, RI 02912, USA.

L. Tang, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, WA 98195, USA.