A nearshore breaker prediction system for Puerto Rico and the United States Virgin Islands in support of beach safety and drowning prevention

Miguel Canals
Center for Applied Ocean Science and Engineering
Caribbean Coastal Ocean Observing System
Department of General Engineering
Department of Marine Sciences
University of Puerto Rico at Mayaguez
Email: miguelf.canals@upr.edu

Julio Morell
Center for Applied Ocean Science and Engineering
Caribbean Coastal Ocean Observing System
Department of Marine Sciences
University of Puerto Rico at Mayaguez

Abstract—**More than half of Puerto Rico's population does not know how to swim and, usually, there are no lifeguards at all on Puerto Ricos beaches. In addition, Puerto Rico has a strongly seasonal cycle in wave heights, and marine conditions can change very quickly as intense swell events arrive. Intense surfzone currents caused by wave-induced pressure gradients pose a threat to beachgoers at hundreds of beaches throughout the region. These are the main facts that account for an average of 25 beach drownings per year. The present study describes the development and implementation of a nearshore breaker prediction system for the PR/USVI region. A high-resolution operational wave model, the CariCOOS Nearshore Wave Model, has been developed in order to adequately resolve wave transformation across the PR/USVI archipelago. The performance of the model for offshore and coastal locations was validated using wave observations from four CariCOOS buoys, with very good results. After ensuring that the model performed satisfactorily at the CariCOOS buoy locations, a field validation experiment was conducted to evaluate model performance in the nearshore region and within the surfzone. A field experiment involving bottom-mounted wave sensors was carried out at the Tres Palmas Marine Reserve in Rincn, Puerto Rico in order to evaluate the performance of one of the high-resolution nested grids. The model was shown to be able to resolve wave transformation with very good results up to just seaward of the surf zone. This shows that the model is able to resolve wave transformation including shoaling, diffraction and refraction at this location. After model validation, a simple method was developed to estimate nearshore breaker heights based on the model output at strategically placed virtual buoys. Each virtual buoy was located just outside the surfzone for each beach, so that the available wave energy flux just seaward of the surfzone could be estimated from the SWAN output. Based on this available wave energy flux, an estimate of the maximum expected breaker heights was obtained using a semi-empirical formulation for breaker heights. While a rigorous validation of breaker heights is very difficult due to the complexity of measuring breaker heights in the surfzone, the breaker height predictions were compared to visually estimated breaker heights at a beach in Rincón, Puerto Rico. While the results of this comparison should be taken with caution, given the subjective nature of visually estimated breaker heights, the results suggest that in general the breaker model can estimate the arrival of high breaker events at this beach with reasonable accuracy. Following this methodology for estimating the range of expected breaker heights, a custom webpage was created in which the range of expected breaker heights as a function of time are provided via a nearshore virtual buoy system at 84 beaches throughout the PR/USVI archipelago.**

I. Introduction

More than half of Puerto Rico's population does not know how to swim and, usually, there are not enough lifeguards or no lifeguards at all on Puerto Rico's beaches. In addition, Puerto Rico has a strongly seasonal cycle in wave heights, and marine conditions can change very quickly as intense swell events arrive. These are the main facts that account for an average of 25 beach drownings per year. One of the gravest dangers to beachgoers are intense surfzone currents which are caused by wave-induced pressure gradients.

Before 2008, real-time data of Puerto Rico's coastal environment was extremely scarce or completely nonexistent. In 2008, NOAA approved funding which led to the development of the Caribbean Coastal Ocean Observing System (CariCOOS). The development of CariCOOS has led to a wealth of real-time data on waves and coastal winds available online (see www.caricoos.org) to beachgoers, thanks to several real-time ocean buoys. In addition, a suite of very high-resolution numerical models provides forecasts of nearshore wave conditions up to several days in advance. In an effort to educate the public on wave induced hazards and to address the wave-induced drowning problem in Puerto Rico, two models have been developed: CariCOOS Nearshore Wave Model and the CariCOOS - Sea Grant Nearshore Breaker Model. The CariCOOS Nearshore Wave Model is a high-resolution operational wave modeling system which is able to predict the spatial distribution of the wave field around Puerto Rico and the United States Virgin Islands. This wave model is the numerical engine behind the CariCOOS - Sea Grant Nearshore Breaker Model, which combines numerical modeling, empirical knowledge, field observations and custom website development to provide the public with an online tool

978-0-933957-43-5 ©2015 MTS

to visualize the presence of potentially dangerous breaking waves at the most popular beaches in Puerto Rico and the United States Virgin Islands. This tool is intended to function as a planning tool which will allow beachgoers, lifeguards and emergency management personnel to make informed decisions regarding beach safety.

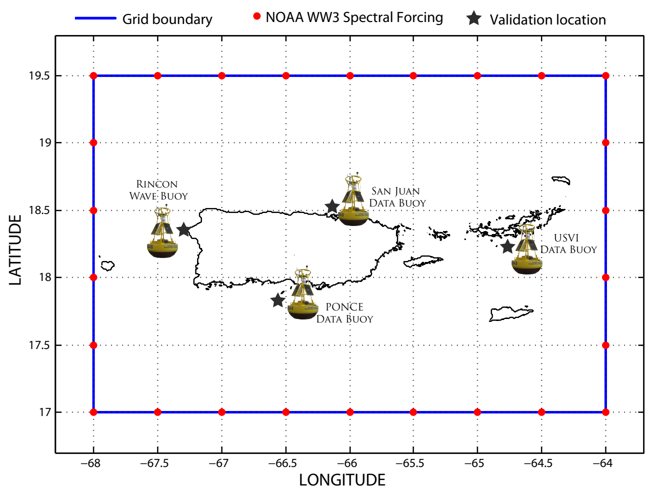

Fig. 1. Schematic of the CariCOOS Nearshore Wave Model grid and boundary forcing. The blue line represents the extent of the model grid at 1 km spatial resolution, and the red dots represent locations at which full two-dimensional spectral wave data from the NOAA NCEP Multigrid WaveWatch III Model [1] is provided as boundary conditions to the SWAN model. The four buoy locations shown represent the sites at which the model was validated.

II. Development of an operational nearshore wave model for accurate prediction of the nearshore wave climate

A. The CariCOOS Nearshore Wave Model

The CariCOOS Nearshore Wave Model (CNWM) is an operational model based on the Simulating Waves Nearshore (SWAN) spectral wave model, which is described in detail in [2] and [3]. Details of the setup and validation of the CariCOOS Nearshore Wave Model may be found in [4] and [5], and only the most important features of the model setup are described herein.

Figure 1 shows a schematic of the PR / USVI parent model grid and boundary conditions. The blue line represents the extent of the model grid at 1 km spatial resolution, and the red dots represent locations at which full two-dimensional spectral wave data from the NOAA NCEP Multigrid WaveWatch III Model [1] is provided as boundary conditions to the SWAN model. The model is run for 120 hours in forecast mode and nine hours in hindcast mode. Surface wind forcing is provided to the model from the National Weather Service National Digital Forecast Database, which consists of three days of wind forecasts from the WRF wind model, run operationally by the National Weather Service San Juan Office, and two days from the NOAA Global Forecast System (GFS, http://www.emc.ncep.noaa.gov/GFS/.php) atmospheric model. Grid bathymetry is obtained from the National Geophysical Data Center Digital Elevation Model for Puerto Rico and the United States Virgin Islands [6]. The model runs operationally twice per day as soon as the NOAA WWIII spectral files for the 00Z and 12Z runs are available online, which usually occurs at around 06Z and 18Z, respectively.

In order to resolve wave propagation and transformation in regions with complex bathymetry and be able to adequately predict breaking wave heights at individual beaches, several high-resolution nested grids were implemented within the CariCOOS Nearshore Wave Model at spatial resolutions ranging from 60 to 240 meters, depending on the size of the domain and the complexity of the bathymetry in each region. Figure 2 shows the location and extent of the 11 very high-resolution nested grids of the CariCOOS Nearshore Wave Model developed as part of the present project. These grids now cover every single meter of inhabited coastline in Puerto Rico and the USVI. The contour plots show sample model output for some of these high-resolution grids. Table I lists the spatial resolution in meters of each nested grid.

B. Model performance at offshore buoys

In order to evaluate model performance, model output from October 29 2012 to January 31 2013 was compared with wave observations at four ocean data buoys owned and maintained by the CariCOOS. The locations of these buoys are shown in Figure 1, and each buoy represents a distinct wave regime within the Puerto Rico / USVI region. The San Juan buoy, located about a kilometer off the city of San Juan in approximately 35 meters depth, is exposed to large North Atlantic swells and the persistent windswell caused by easterly trade winds. The Rincón wave buoy is located about a mile off the coast and is relatively protected from easterly windswell but is fully exposed to long period winter swells entering the Mona Passage from the northwest, north and northeast. The USVI buoy is located about nine miles south of St. John in about 40 meters depth and is significantly sheltered from winter swells by St. Thomas and St. John to the north, but is fully exposed to windswell from easterly trade winds as well as to long period swells which enter the Caribbean through the Anegada Passage. Finally, the Ponce buoy is located south of Puerto Rico and is mostly affected by windswell, but is completely sheltered from winter swells. All four buoys are periodically subject to strong wave events from tropical storms and hurricanes.

Figure 3 shows a comparison between the observed and simulated significant wave height and peak period at the four CariCOOS buoys. Visual inspection suggests that the model reproduces correctly the wave heights and peak periods of significant wave events, although the model underestimates the wave height for several major events, especially in the San Juan and Rincón buoys. This discrepancy could be due to an underestimation caused by Wavewatch III boundary conditions, or from local wind effects. Figure 4 shows scatter plots of observed vs. simulated significant wave height (left column) and observed vs. simulated peak wave periods (right column) at the four CariCOOS buoys. For the significant wave

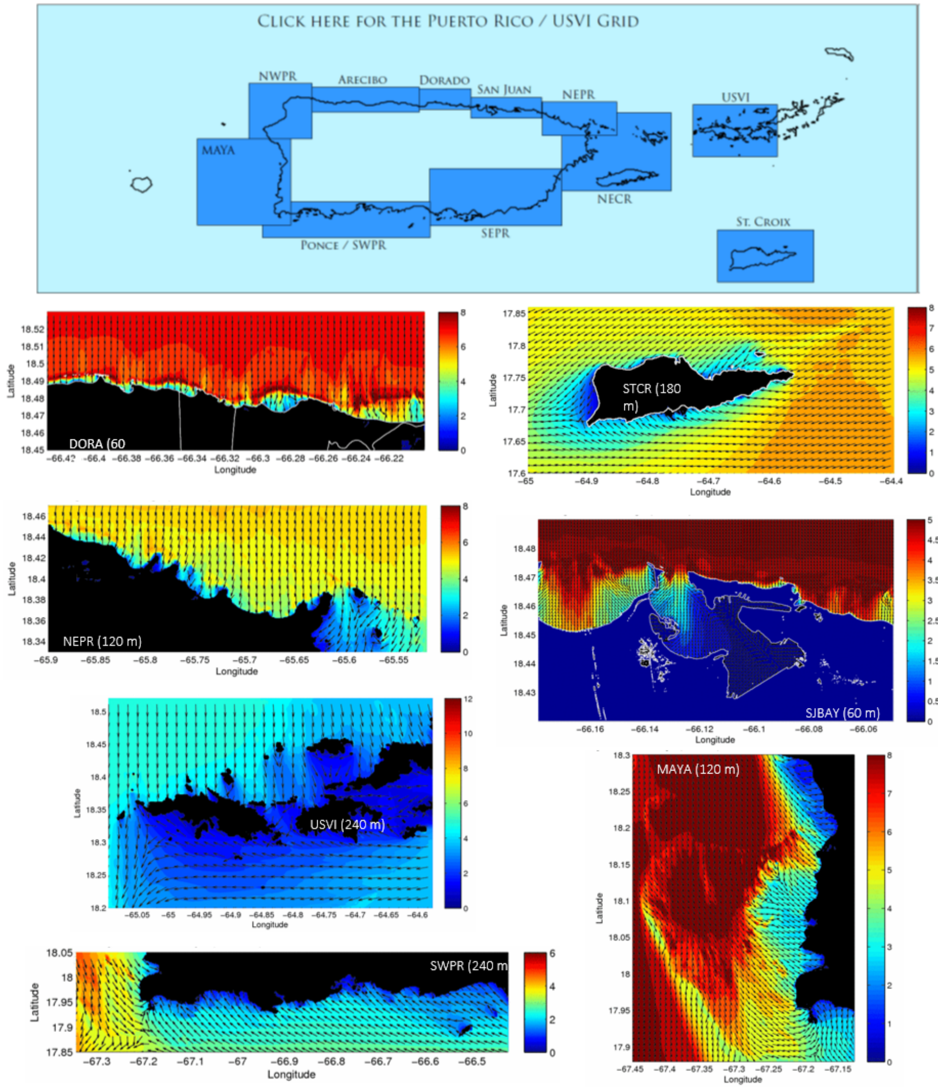

Fig. 2. Location and extent of the 11 high-resolution nested grids of the CariCOOS Nearshore Wave Model developed as part of the present project. As of March 2015 these grids now cover every single meter of inhabited coastline in Puerto Rico and the USVI.

height scatter plots the color of each data point represents the observed peak period at that instance. The color of each data point in the peak wave period scatter plots (right column) represents the observed significant wave height at that instance. This visualization shows how the model behaves as a function of the observed sea state. The solid black line in each plot represents the linear regression which best represents the model-data relationship, while the gray dashed line represents a perfect fit. In general, the model underestimate wave heights at all four buoys, with a more pronounced underestimation at Rincón. The predictions of peak wave periods are generally worse for low wave periods, probably due to the challenges associated with predicting the coastal wind field, including the daily sea breeze cycle. Table II shows the model validation statistics for both significant wave height and peak wave period for each buoy location.

C. Model performance very near shore and in the surf zone

The CariCOOS Nearshore Wave Model was validated in January 2013 during strong winter swells in order to evaluate its performance in predicting nearshore wave heights. A model validation experiment was conducted in which four wave observing assets were used: the CariCOOS Rincón Wave Buoy (a permanent asset), two pressure sensors (PS1 and PS2) and an Acoustic Wave and Current Meter (AWAC). The sensors were deployed on January 11 2013 and were recovered on February 14 2013. Several long period winter swells were sampled during this period, allowing for model validation over a broad range of sea states. The validation experiment took place at the Tres Palmas Marine Reserve (TPMR), located within the domain of the Northwestern Puerto Rico (NWPR) high-resolution nested grid (see Figure 2). This study site is well known for its very large breaking waves, craved by surfers from around the world during the winter months. The location

Nested Grid Name	Spatial Resolution (m)
NWPR	120
AREC	180
DORA	60
SJBAY	60
NEPR	120
NECR	240
SEPR	240
PONCE	240
MAYA	120
USVI	240
STCR	180

TABLE I

SPATIAL RESOLUTION OF THE NESTED GRIDS SHOWN IN FIGURE 2.

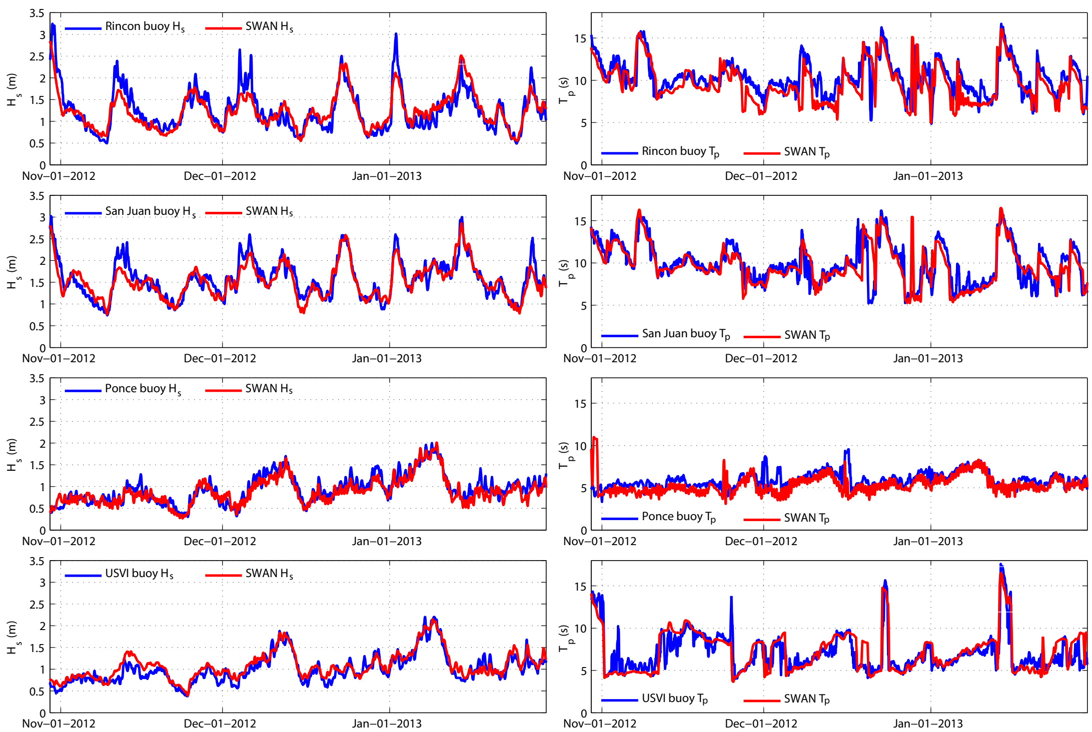

Fig. 3. Comparison between observed (blue line) and simulated (red line) significant wave height (left column) and peak period (right column) at the four CariCOOS buoys: Rincón (top row), San Juan (second row from top), Ponce (third row from top) and USVI (bottom row).

of each sensor is shown in Figure 6. Figure 5 shows the approximate location of the AWAC and the pressure sensors during a large winter swell on January 14, 2013. The AWAC was located outside of the surf zone, PS1 was located just offshore of the breaking point, and PS2 was located inside the breaker region on this particular day. Note that the offshore extent of the surf zone varies widely depending on incoming wave conditions, so that on smaller days PS2 was also located outside the surf zone.

Figure 7 shows a time series of the comparison between the model-predicted and observed significant wave height at the sensor locations. At the Rincón buoy the model does a very good job of reproducing the wave field. At the AWAC and PS1 locations the model also successfully reproduces most of the wave events. Note the significant shoaling captured by both the model and the observations from the AWAC site to the PS1 site during the January 14 swell event (same as the one pictured in Figure 5). After February 7 2013 the PS2 sensor stopped collecting data due to battery depletion. At the PS2 location, Figure 7 shows that the operational model was unable to correctly resolve wave dissipation due to breaking, and overestimates the wave height at the PS2 location, most notably for the January 14, January 27 and February 12 swell events. Since the PS2 sensor was located well inside the surf zone for these large wave events, it is the authors' hypothesis that the SWAN model does not accurately reproduce the dissipation of mechanical energy due to wave breaking due to the fact that SWAN assumes a spilling breaker model. At the study site, some waves are plunging waves. In addition, the horizontal resolution of 120 meters for the NWPR grid

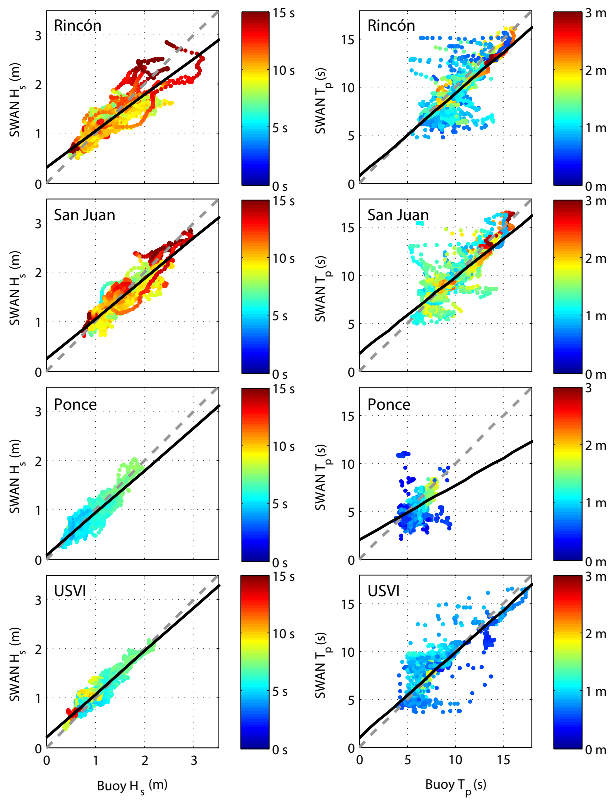

Fig. 4. Left column: Scatter plots of observed vs. simulated significant wave height at the four CariCOOS buoys: Rincón (top), San Juan (second from top), Ponce (third from top) and USVI (bottom); the color of each data point represents the observed peak period at that instance. Right column: Same as the left column but for the peak wave period; the color of each data point represents the observed significant wave height at that instance. The solid black line in each plot represents the linear regression which best represents the model-data relationship, while the gray dashed line represents a perfect fit.

	H_s		
	r	r^2	RMSE (m)
Rincón	0.86	0.75	0.24
San Juan	0.90	0.815	0.19
Ponce	0.91	0.835	0.15
USVI	0.93	0.865	0.14
	T_p		
	r	r^2	RMSE (s)
Rincón	0.76	0.58	1.64
San Juan	0.80	0.63	1.48
Ponce	0.46	0.21	1.14
USVI	0.83	0.69	1.39

TABLE II
MODEL VALIDATION STATISTICS AT EACH BUOY LOCATION FOR SIGNIFICANT WAVE HEIGHT (H_s) AND PEAK WAVE PERIOD (T_p).

is likely still too coarse to reproduce the energy dissipation over a surf zone that is, at most, 200-300 meters wide in the cross-shore direction during these specific events.

While better results at the PS2 location (inside the surf zone) could have been obtained with a higher spatial resolution, the aim of the present study was to develop a fully operational wave model covering all PR/USVI beaches. Spatial resolution higher than 120 meters, at least for the NWPR grid, was prohibitive due to computational limitations. However, given that the aim of the present project was to be able to predict breaker heights at the seaward edge of the surfzone (e.g., at the PS1 location), and not the heights of individual waves (or bores) shoreward of the surfzone (a much more involved task), the authors deem the model to be adequate for developing a nearshore breaker prediction system which can predict the maximum breaker heights to be expected at a particular beach on a given day.

The fact that the operational SWAN model can sometimes overestimate wave heights seaward of the surfzone can be taken as an additional safety factor, thus resulting in conservative estimates of breaker heights (from a beach safety standpoint, so larger waves than in reality). For beaches which are protected by large offshore coral reef formations, such as those found in beaches of San Juan and Carolina, the spatial resolution of the model for this region (the SJBAY grid) was increased to 60 meters to better resolve wave energy dissipation. However, the model was not validated at these beaches since such validation experiments were out of the scope of the present project. Future work should focus on further validation of the CariCOOS Nearshore Wave Model at beaches located seaward of offshore barrier reefs. Ongoing work by CariCOOS is focused on further improving our wave models suite for these applications.

III. Development of the CariCOOS - Sea Grant Nearshore Breaker Model

The development, implementation and validation of the operational CariCOOS Nearshore Wave Model was presented in the preceding section. This numerical tool was shown to be able to adequately reproduce the wave field around Puerto Rico and the USVI both in offshore conditions and just seaward of the surf zone. Once this goal was completed, the project focused on developing an online tool able to estimate breaker heights at the most popular beaches of Puerto Rico and the USVI. During the design stage of this tool, named the CariCOOS - Sea Grant Nearshore Breaker Model, the following design criteria were used:

- The model is intended to be used as a beach safety tool to be used by beachgoers, lifeguards emergency management personnel, etc.
- The model needed to be able to adequately estimate the minimum and maximum breaking wave heights at individual beaches.
- More than a tool by itself, the model needed to translate the wealth of wave data provided by the SWAN wave model into an user-friendly online tool
- There was a need to use a simple method to estimate breaking heights based on the SWAN output for individual beaches, so that this method could be easily modified and calibrated with field observations and visual estimates.

The next section describes the methodology for computing breaker heights using the SWAN wave parameters.

A. Estimating Breaker Heights

Within the validated wave model described in the preceding section, a network of virtual buoys provides forecasts of 3 to 5 days in advance of wave parameters such as significant wave height, swell wave height, mean wave period, peak wave period, mean wave direction and peak wave direction. A total of 84 virtual buoys (as of March 2015) were implemented at each of the 84 beaches at which breaker height predictions were desired. Special care was taken when implementing a virtual buoy for a specific beach. Factors such as the local bathymetry, potential seaward extent of the surfzone during a storm, the spatial resolution of the nested grid at which the beach was located, etc., were considered in determining the best suited location for a virtual buoy such that the breaker height predictions were representative of the conditions at each beach. It should be noted that due to the wide variability in beach types and the complex geomorphology and bathymetry of the seabed around PR/USVI, each virtual buoy location has a different depth. However, the effects of local water depth in predicting the breaker heights at each beach is taken into account by computing the wave energy flux at each virtual buoy, as will be explained below.

There has been significant research conducted in order to predict nearshore breaking wave heights as a function of offshore wave conditions [7]. A simple yet elegant semi-empirical relationship was obtained by [8], who showed via laboratory experiments that the height of breaking waves Hb could be estimated using the deep water wave height and wave period as follows:

$$Hb = 0.39 g^{\frac{1}{5}} \cdot (T_\infty \cdot {H_\infty}^2)^{\frac{2}{5}} \tag{1}$$

where the ∞ subscript denotes deep water wave conditions. This relationship only takes into account wave shoaling and depth-induced breaking and does not take into account the effects of wave refraction, diffraction, bottom friction, and was not tested for bottom slopes larger than 6% [8]. However, it is a very useful relationship since the SWAN wave model already takes into account most of these effects to propagate and transform the wave field to the virtual buoy location. Even though there are more involved formulations for predicting wave heights [9], and the fact that the relationship shown above can sometimes underestimate breaker heights on steep sloped beaches [9], the simplicity of this equation is a good starting point for breaker height estimation. This simple relationship for breaker height prediction was derived using linear wave theory and the concept of conservation of wave energy flux, in which the wave energy flux in deep water is equal to the wave energy flux at the breaking point:

$$(ECg)_b = (ECg)_\infty \tag{2}$$

where the subscript b corresponds to the breaking point, E is the wave energy density per unit area and C_g is the wave group speed. The wave energy density per unit area E is given by:

Fig. 5. Approximate location of the sensors used during the validation experiment during a large winter swell on January 14, 2013. The sensors were in the water on this same day and successfully sampled this wave event.

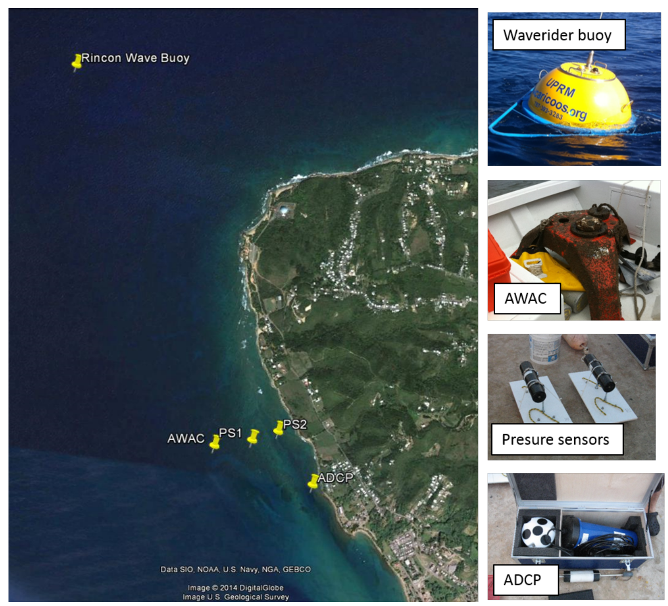

Fig. 6. Location of the sensors during the validation experiment conducted at the Tres Palmas Marine Reserve in January-February 2013.

$$E = \frac{1}{8} \rho g H^2 \tag{3}$$

where H is the local wave height, ρ the seawater density, and g the gravitational constant. The wave group speed, C_g, is given by:

$$Cg = \frac{1}{2} \left\{ 1 + \frac{4\pi d/L}{\sinh(4\pi d/L)} \right\} \frac{L}{T} \tag{4}$$

where d is the local water depth and L is the local wavelength, which is obtained by solving the full wave dispersion relation:

$$\omega^2 = gk \tanh kd \tag{5}$$

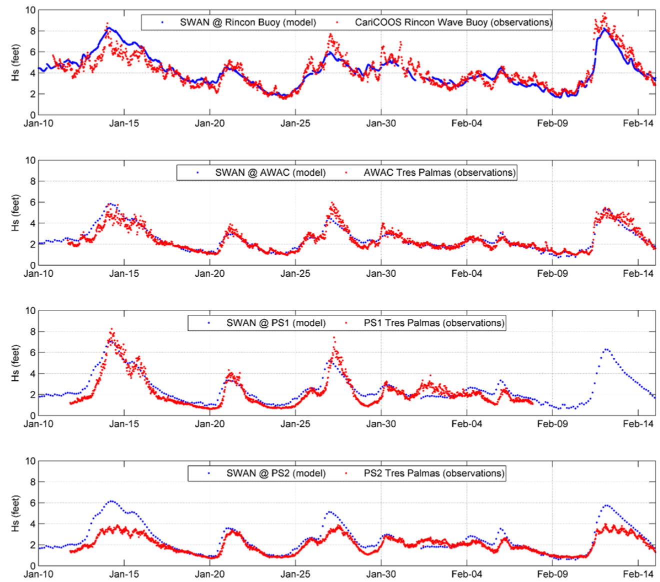

Fig. 7. Comparison between SWAN predictions and observed wave height at the four sensors.

where $\omega = 2\pi/T$ is the wave angular frequency and $k = 2\pi/L$ is the angular wavenumber.

In order to estimate breaking wave heights, a similar approach was used in the present study in which the time-dependent wave energy flux at each virtual buoy is computed using equation 2 and then used to calculate the equivalent offshore wave height so that equation 1 by [8] can be used to estimate the time-dependent breaking wave heights. The SWAN model output at each virtual buoy is characterized by the predicted significant wave height Hs_i, mean wave period Tm_i, peak wave period Tp_i, the swell wave height Hsw_i, the mean wave direction θm_i, and peak wave direction θp_i. The i subscript indicates that this is the model estimated wave parameter at a specific nearshore virtual buoy. The time-dependent wave-energy flux at each virtual buoy is then calculated as:

$$P_i(t) = E_i(t) Cg_i(t) \tag{6}$$

where

$$E_i(t) = \frac{1}{8}\rho g H s_i^2 \tag{7}$$

and

$$Cg_i(t) = \frac{1}{2}\left\{1 + \frac{4\pi d_i/L_i}{\sinh(4\pi d_i/L_i)}\right\}\frac{L_i}{Tp_i} \tag{8}$$

where Cg_i is the group speed at the virtual buoy location, d_i is the water depth at the virtual buoy and L_i is the wavelength corresponding to the SWAN-predicted peak wave period Tp_i, computed using the full dispersion relation given in equation 5. Using equation 2, the equivalent deep water wave height H_∞ with an energy flux equal to the energy flux predicted by SWAN at the virtual buoy location is given by

$$H_\infty = Hs_i\sqrt{\frac{Cg_i}{Cg_\infty}} \tag{9}$$

where Cg_∞ is the deep water group speed corresponding to the SWAN-predicted peak wave period at the virtual buoy location, Tp_i. Using this equivalent deep water wave height, it is then possible to estimate the breaking wave height based on the available wave energy flux at the virtual buoy location, using [8]'s relationship:

$$Hb_i = 0.39 g^{\frac{1}{5}} \cdot (T_i \cdot H_\infty{}^2)^{\frac{2}{5}} \tag{10}$$

The rationale for using the above equation for estimating the breaking wave heights shoreward of the location of each virtual buoy is that the SWAN wave model will already have simulated the propagation and transformation of the wave field, causing significant changes in the local wave energy flux due to the effects of wave refraction, diffraction, bottom friction, surface wind stress, and other physical mechanisms of wave energy dissipation. The local wave energy flux at each virtual buoy, P_i, is thus a measure of the wave energy available to generate breaking waves at each beach. This energy will be larger or smaller than the offshore wave energy flux depending on the effects of bathymetry, wave shadowing, etc.

Equation 10, as presented, provides an estimate of the significant height of breaking waves. For beach safety and recreational purposes, the significant breaking wave height, $Hb_{1/3}$, will not necessarily be the most useful value for a surfer or beachgoer. From a beach safety perspective, providing such an estimate would significantly underestimate the potential danger of breaking waves. The average of the top 10% or 1% of the waves during a specific time period could be a more useful estimate of actual breaking wave heights [10]. These quantities are given by:

$$Hb_{1/10} = 1.27 Hb_{1/3} \tag{11}$$

$$Hb_{1/100} = 1.67 Hb_{1/3} \tag{12}$$

In general, it is very difficult to validate estimates of breaking wave heights in the field, and most of the breaking wave height research has been conducted in the laboratory [7]. In order to determine if the formulae presented above provide reasonable estimate of breaker heights, the breaker height model predictions, $Hb_{1/10}$ and $Hb_{1/100}$, were compared to a dataset of visually estimated surf heights from the Rincón Surf Report web site: http://rinconsurfreport.com/. The owner of this surf report service provides daily surf reports in the Rincón area, mostly at Domes Beach, although reports are sometimes provided for nearby beaches. Since Domes Beach is one of the 84 beaches at which breaker height predictions are provided in the CariCOOS - Sea Grant Nearshore Breaker Model, more than two years of this dataset were used and compared to more than two years of SWAN wave data. The visually estimated breaker heights from Rincón Surf Report (RSR) were translated to crest to through values in feet using the visual scale used by surfers (http://www.surfline.com/surf-science/wave-heights---forecaster-blog_22495/), as follows:

0' = flat
1' = ankle-shin high
2' = knee-thigh high
3' = waist-belly high
4' = chest-shoulder high
5' = head high
6' = 1 foot overhead
8' = 3' overhead
10' =5' overhead or Double Overhead faces
12' = Double Overhead+ faces
15'-20' = Triple Overhead +

The larger visual estimates will carry the largest uncertainty. In addition, there is considerable uncertainty regarding the relationship between the visually estimated surf heights conducted by surfers and the statistical wave parameters such as significant wave height, etc. [10] report that the upper limit of these visual estimates usually correspond to either $Hb_{1/10}$ or $Hb_{1/100}$, which correspond to the breaker heights of the top 10% or 1% waves, respectively, during the observation period. It should be noted that the visually estimated breaker heights can be highly subjective and the scale used can vary widely from one observer to another, and that the results should be treated with caution. However, the RSR estimates has provided a valuable dataset in order to gauge the performance of the breaker height predictions using the equivalent offshore wave height method described above.

Figure 8 shows a comparison between the model estimated breaker heights ($Hb_{1/10}$ in blue and $Hb_{1/100}$ in cyan) and the visually estimated breaker heights (red points) inferred from the Rincón Surf Report database. Visual inspection reveals that the model predictions follow the general trend of the observations, except for the largest wave events, in which the model underestimates the visually inferred breaker heights. Given the nature of the observations dataset, it is difficult to determine the reason for this discrepancy. It could be due to the fact that when the waves are very large, the surf height observations are generally obtained at Tres Palmas and not at Domes Beach. It is well known that during very large wave events, wave refraction causes very large waves to focus and break on Tres Palmas and that these waves can be larger than those found at Domes Beach during long period swells. Another reason for the discrepancy during the largest events could be due to an underestimate of the wave height by the CariCOOS Nearshore Wave Model, as was noted in the previous section in Figure 3. However, given the highly subjective nature of visually estimated breaker heights, the hypotheses formulated above cannot be confirmed or rejected and remain as speculation. Figure 9 shows a scatter plot of the relationship between the visually estimated breaker heights from RSR and the model estimated breaker heights ($Hb_{1/10}$ in blue and $Hb_{1/100}$ in red) and the corresponding least squares linear fit. The gray dashed line represents a hypothetical perfect fit. It is evident that both $Hb_{1/10}$ and $Hb_{1/100}$ overestimate the breaker heights for smaller events and underestimate the breaker heights for larger events. However, given the highly subjective nature of visually estimated breaker heights, these results should be treated with caution.

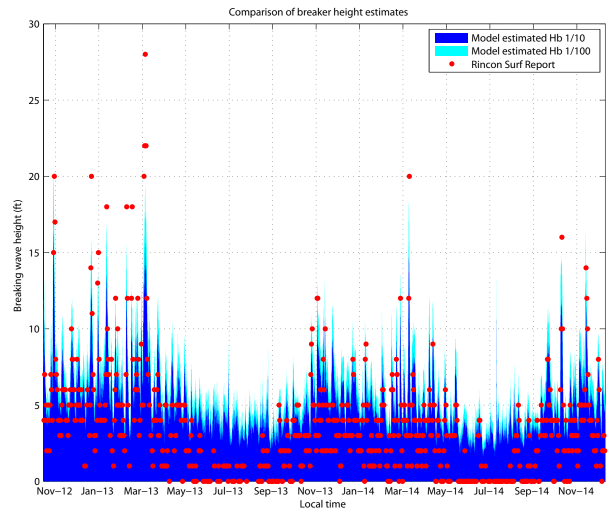

Fig. 8. Comparison between model estimated breaker heights ($Hb_{1/10}$ in blue and $Hb_{1/100}$ in cyan) and the visually estimated breaker heights (red points) inferred from the Rincón Surf Report database.

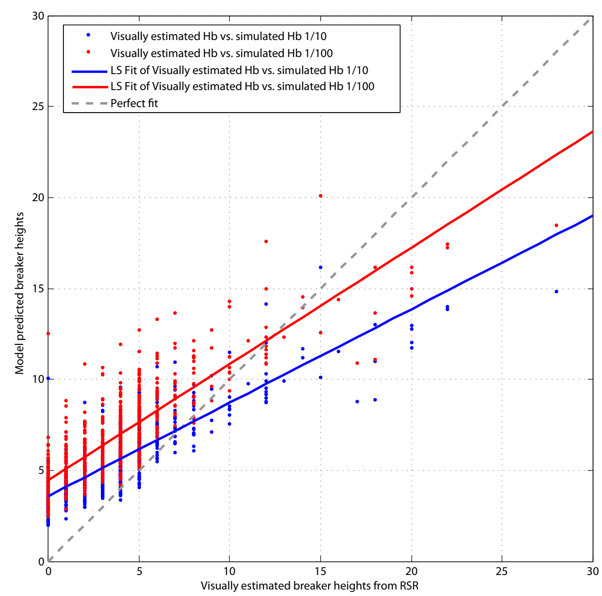

Fig. 9. Scatter plot showing the relationship between the visually estimated breaker heights from RSR and the model estimated breaker heights ($Hb_{1/10}$ in blue and $Hb_{1/100}$ in red) and the corresponding least squares linear fit. the gray dashed line represents a hypothetical perfect fit. It is evident that both $Hb_{1/10}$ and $Hb_{1/100}$ overestimate the breaker heights for smaller events and underestimate the breaker heights for larger events. However, given the highly subjective nature of visually estimated breaker heights, these results should be treated with caution.

Based on the results discussed above, until a better model validation effort is carried out, the $Hb_{1/100}$ estimate has been determined to be the best estimator of the breaking wave heights and has been implemented as the upper bound for the time-dependent breaker heights in the CariCOOS Sea Grant Nearshore Breaker Model. The lower bound of the breaking wave heights has been chosen as the significant wave height Hs_i provided by SWAN at each virtual buoy location. While an empirical relationship between the SWAN wave parameters and the visually estimated surf heights could in theory be obtained, this approach was not used since it is very likely that such an empirical relationship would only be valid at Domes Beach and could not be extrapolated to the other 84 beaches in PR/USVI within the breaker prediction system. On the other hand, the [8] model implemented herein has a solid theoretical foundation and is likely to be robust throughout the region.

Figure 10 shows an example of a breaker height virtual buoy for Jobos Beach. Besides the range of expected breaker heights, the virtual buoy also provides water level and wind predictions for each beach. Similar predictions are available for 84 beaches in PR/SUVI in the CariCOOS - Sea Grant Nearshore Breaker Model webpage: http://www.caricoos.org/Nearshore_Breaker_Model/.

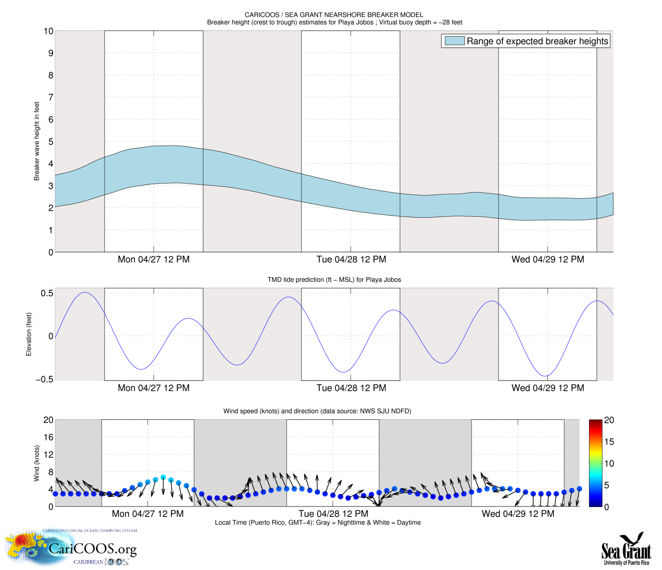

Fig. 10. Sample output of the breaker height virtual buoy for Jobos Beach. Besides the range of expected breaker heights, the virtual buoy also provides water level and wind predictions for each beach. Similar predictions are available for 84 beaches in PR/USVI in the CariCOOS - Sea Grant Nearshore Breaker Model webpage.

IV. Concluding remarks

A high-resolution operational wave model, the CariCOOS Nearshore Wave Model, was developed as part of the present project. The details of the model implementation and validation were discussed in section II. In summary, the model was able to adequately resolve wave transformation across the PR/USVI archipelago. The performance of the model for offshore / coastal locations was validated using wave observations from four CariCOOS buoys, with very good results.

After ensuring that the model performed satisfactorily at the CariCOOS buoy locations, a field validation experiment was conducted to evaluate model performance in the nearshore region and within the surfzone. A field experiment involving bottom-mounted wave sensors was carried out at the Tres Palmas Marine Reserve in order to evaluate the performance of one of the high-resolution nested grids at 120 meter resolution. The model was shown to be able to resolve wave transformation with very good results up to just seaward of the surf zone. This shows that the model is able to resolve wave transformation including shoaling, diffraction and refraction at this location. Comparison with a sensor located inside of the surfzone during large wave events showed that the operational model was unable to correctly resolve wave dissipation due to breaking, and overestimates the wave height at this location. It is the authors' hypothesis that the SWAN model does not accurately reproduce the dissipation of mechanical energy due to wave breaking due to the fact that SWAN assumes a spilling breaker model. In addition, the horizontal resolution of 120 meters for the NWPR grid is likely still too coarse to reproduce the energy dissipation over a surf zone that is, at most, 200-300 meters wide in the cross-shore direction during these specific events. While better results inside the surf zone could have been obtained with a higher spatial resolution, the aim of the present study was to develop a fully operational wave model covering all PR/USVI beaches. Spatial resolution higher than 120 meters, at least for the NWPR grid, was prohibitive due to computational limitations. However, given that the aim of the present project was to be able to predict breaker heights at the seaward edge of the surfzone, and not the heights of individual waves (or bores) shoreward of the surfzone (a much more involved task), the authors deem the model to be adequate for developing a nearshore breaker prediction system which can predict the maximum breaker heights to be expected at a particular beach on a given day.

Section III described the development of a simple method to estimate nearshore breaker heights based on the output of the CariCOOS Nearshore Wave Model at strategically placed virtual buoys. Each virtual buoy was located just outside the surfzone for each beach, so that the available wave energy flux just seaward of the surfzone could be estimated from the SWAN data. Based on this available wave energy flux, an estimate of the maximum expected breaker heights was obtained using a semi-empirical formulation for breaker heights [8]. While a rigorous validation of breaker heights is very difficult due to the complexity of measuring breaker heights in the surfzone, the breaker height predictions were compared to visually estimated breaker heights at a beach in Rincón, Puerto Rico. While the results of this comparison should be taken with caution, given the subjective nature of visually estimated breaker heights, the results suggest that in general the breaker model can estimate the arrival of high breaker events at this beach. Following this methodology for estimating the range of expected breaker heights, a custom webpage was created in which the range of expected breaker heights as a function of time are provided via a nearshore virtual buoy system. The model is now operational and the reader may access the daily predictions at http://www.caricoos.org/Nearshore_Breaker_Model/.

As the computational capabilities of CariCOOS improve, the performance of the breaker model described herein should improve as nested grids are implemented at higher spatial resolution. CariCOOS has adopted the breaker model as a permanent modeling tool and is committed to maintaining and improving the model in perpetuity in support of CariCOOS' and UPR Sea Grant's mission to better educate the public on beach hazards and the drowning problem in Puerto Rico and USVI beaches. Finally, some recommendations for future work are as follows:

- The CariCOOS Nearshore Wave Model was validated extensively throughout the development period. However, further validation should be conducted as nested grids are implemented at even higher spatial resolution as computational capabilities allow.
- One of the main factors that could improve model performance for both wave statistics and breaker heights is the implementation of better wind models for PR/USVI. While the NDFD wind database used to force the wave model described in this report does a good job in predicting local wind effects, local seabreeze and topographic effects become very important in the wave climate of some beaches, and a higher resolution wind model would very likely improve the wave model performance. CariCOOS is already implementing a 1 km resolution WRF wind model which should help in this effort.
- Further validation of the breaker height predictions should be conducted using more rigorous methods of breaker height estimation such as video imagery or by deploying more sensors across the surfzone, especially in beaches which are located inshore of fringing or barrier reef formations such as the beaches in Isla Verde in Carolina and the Condado area in San Juan.

Acknowledgments

This project was funded by the UPR Sea Grant Program (Grant R-124-1-12) and by the Caribbean Coastal Ocean Observing System (Grant NA11NOS0120035). Carlos Anselmi from the NWS San Juan Weather Forecast Office was the lead developer of the first version of the CariCOOS Nearshore Wave Model.

References

[1] A. Chawla, H. L. Tolman, V. Gerald, D. Spindler, T. Spindler, J.-H. G. M. Alves, D. Cao, J. L. Hanson, and E.-M. Devaliere, "A multigrid wave forecasting model: A new paradigm in operational wave forecasting," *Weather and Forecasting*, vol. 28, p. 10571078, 2013.

[2] N. Booij, R. C. Ris, and L. Holthuijsen, "A third generation wave model for coastal regions. Part 1: Model description and validation," *Journal of Geophysical Research*, vol. C4, no. 104, pp. 7649–7666, 1999.

[3] The SWAN Team, "SWAN user manual," Delft University of Technology, Technical Report, 2012.

[4] C. Anselmi, M. Canals, J. Morell, J. Gonzalez, J. Capella, and A. Mercado, "Development of an operational nearshore wave forecast system for Puerto Rico and the U.S. Virgin Islands," *Journal of Coastal Research*, vol. 28, no. 5, pp. 1049–1056, 2012.

[5] M. Canals, J. Morell, J. Corredor, and S. Leonardi, "Expanding the Caribbean Coastal Ocean Observing System into the nearshore region," in *Oceans, 2012*, Oct 2012, pp. 1–4.

[6] L. A. Taylor, B. W. Eakins, R. R. Warnken, K. S. Carignan, G. F. Sharman, and P. W. Sloss, "Digital elevation models for San Juan and Mayagüez, Puerto Rico: Procedures, data sources and analysis," NOAA National Geophysical Data Center, Boulder, CO, Technical Report, 2006.

[7] D. H. Peregrine, "Breaking waves on beaches," *Annual Review of Fluid Mechanics*, vol. 15, no. 1, pp. 149–178, 1983.

[8] P. D. Komar and M. K. Gaughan, "Airy wave theory and breaker height prediction," in *Proceedings from the 13th Conference of Coastal Engineering*, Vancouver, British Columbia, Canada, July 1972.

[9] J. P. LeRoux, "A simple method to determine breaker height and depth for different deepwater wave height/length ratios and sea floor slopes," *Coastal Engineering*, vol. 54, pp. 271–277, 2007.

[10] P. C. Caldwell and J. P. Aucan, "An empirical method for estimating surf heights from deep water significant wave heights and peak periods in coastal zones with narrow shelves, steep bottom slopes and high refraction," *Journal of Coastal Research*, vol. 23, pp. 1237–1244, 2007.