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Evaluation of wave runup predictions from numerical and parametric models

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ABSTRACT

Wave runup during storms is a primary driver of coastal evolution, including shoreline and dune erosion and barrier island overwash. Runup and its components, setup and swash, can be predicted from a parameterized model that was developed by comparing runup observations to offshore wave height, wave period, and local beach slope. Because observations during extreme storms are often unavailable, a numerical model is used to simulate the storm-driven runup to compare to the parameterized model and then develop an approach to improve the accuracy of the parameterization. Numerically simulated and parameterized runup were compared to observations to evaluate model accuracies. The analysis demonstrated that setup was accurately predicted by both the parameterized model and numerical simulations. Infragravity swash heights were most accurately predicted by the parameterized model. The numerical model suffered from bias and gain errors that depended on whether a one-dimensional or two-dimensional spatial domain was used. Nonetheless, all of the predictions were significantly correlated to the observations, implying that the systematic errors can be corrected. The numerical simulations did not resolve the incident-band swash motions, as expected, and the parameterized model performed best at predicting incident-band swash heights. An assimilated prediction using a weighted average of the parameterized model and the numerical simulations resulted in a reduction in prediction error variance. Finally, the numerical simulations were extended to include storm conditions that have not been previously observed. These results indicated that the parameterized predictions of setup may need modification for extreme conditions; numerical simulations can be used to extend the validity of the parameterized predictions of infragravity swash; and numerical simulations systematically underpredict incident swash, which is relatively unimportant under extreme conditions.

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1. Introduction

Hurricanes and other large storms can cause extensive changes to coastal topography, including shoreline erosion, destruction of protective dunes, creation of large overwash deposits, and opening of new inlets. These changes can have a profound impact on coastal environments and may increase coastal vulnerability to future storms. The type and magnitude of barrier island response to storms is dependent, in part, on the interactions between beach morphology and the oceanographic forces associated with waves and storm surge. The shoreline manifestation of these forces is wave runup, which can, in general, be estimated from knowledge of offshore wave height and period (or wave spectra) and nearshore topography, including the slope of the intermittently wet and dry foreshore (Bowen et al., 1968; Kobayashi et al., 1990; Reniers et al., 2002). Using data sets with numerous observations of offshore wave conditions and synchronous runup measurements, empirical parameterizations have been developed to predict the magnitude of runup and its components, setup and swash (Holman, 1986; Nielsen and Hanslow, 1991; Ruessink et al., 1998; Ruggiero et al., 2004; Stockdon et al., 2006). The Stockdon et al. (2006) parameterization (hereinafter referred to as S2006) in particular has been shown to support skillful predictions of coastal changes in the vicinity of hurricane landfall (Plant and Stockdon, 2012; Stockdon et al., 2007), despite not having been originally formulated using storm conditions. However, the accuracy of parameterized swash and setup during extreme storm conditions has not been examined. Evaluating the S2006 parameterization under extreme storm conditions, when observational data are typically unavailable, requires a new approach.

The S2006 parameterizations were determined by fitting a large number of observations to a statistical model based on observed offshore significant wave height (H), dominant wave period, and foreshore beach slope (β). The parameterizations are

$$\overline{\eta} = 0.35\,\beta\,\sqrt{HL}, \tag{1a}$$

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$$S_{in} = 0.75\,\beta\,\sqrt{HL}, \text{ and} \tag{1b}$$

$$S_{ig} = 0.06\,\sqrt{HL}, \tag{1c}$$

where $\overline{\eta}$ is the wave setup, defined as the time-average of the non-tidal water level fluctuations at the shoreline. S_{in} and S_{ig} are the significant swash heights in the incident (frequency > 0.05 Hz) and infragravity bands (frequency < 0.05 Hz), respectively, defined as four times the standard deviation of the water levels within each frequency band. Wave length (L) is computed from local wave period. Local wave height is reverse shoaled to deep water to obtain an estimate of offshore wave height (H). The coefficients estimated as part of the parameterization development were based on observations from a restricted range of conditions (Stockdon and Holman, 2011). Specifically, the maximum offshore wave height was 4 m; therefore, the parameterization does not include extreme conditions associated with major storms or hurricanes when wave heights reach 7 m or more (Doran et al., 2013; Stockdon et al., 2012, 2013).

The importance of understanding and quantifying the accuracy of runup predictions under extreme conditions is twofold. First, the predictions of sediment transport in detailed numerical models and of morphologic change in statistical approaches are based on calibration. We want to know if these calibrations are correcting for underlying prediction errors in hydrodynamic processes. Second, the predictions of extreme water levels that include wave runup are required for more accurate assessments of coastal hazards (Stockdon et al., 2012). Wave-induced water levels can be a direct threat to people, infrastructure, and ecosystems; however they are not routinely included in the analysis of coastal hazards in, for instance, the weather forecasting community. Understanding the accuracy of runup predictions during extreme wave events will help to inform and improve assessments of potential hazards to people and wildlife that build communities (e.g., roads, houses, nests) in dynamic coastal environments that shift and change with each storm.

Wave runup processes are not easy to measure, particularly under extreme conditions. Powerful wave forces and significant beach change can damage observing equipment or introduce uncertainty in the underlying topographic elevations needed to understand the runup processes. One approach to circumventing observational challenges is to numerically simulate runup. This has been done using the XBeach model, which couples runup to sediment transport and dune erosion (Roelvink et al., 2009). The model does not resolve incident-frequency motions but directly computes setup and low-frequency wave motions which tend to dominate the runup processes during dissipative storm conditions (Roelvink et al., 2009; Ruggiero et al., 2004; Thornton and Guza, 1982). Model predictions have been compared to observed beach and dune changes to test the accuracy of the coupled runup and sediment transport formulations with skillful results (McCall et al., 2010; Roelvink et al., 2009; Splinter and Palmsten, 2012).

In order to use XBeach to simulate storm waves and runup for the purpose of extending runup parameterizations to more energetic wave conditions, the accuracy of the modeled runup must be evaluated. Here, we conduct a comparison and sensitivity study to assess the accuracy of XBeach runup predictions across a range of conditions that have corresponding runup measurements. The objective is to evaluate the model skill at predicting setup, incident swash, and infragravity swash. Then, using this information, we can test the application of the S2006 parameterizations to extreme conditions and compare them with numerical simulations. Finally, we present a methodology for improving statistical parameterizations based on assimilating model results and observations.

2. Methods

XBeach runup predictions were evaluated using data from the SandyDuck field experiment (Stockdon and Holman, 2011) at the U.S. Army Corps of Engineers Field Research Facility (FRF) located in Duck, NC, in October 1997. Runup data were collected over a 9-day period between October 16 and 24. These data have been presented elsewhere (e.g. Stockdon et al. (2006)), hence, we provide only a brief summary and then describe the XBeach model and runup extraction.

2.1. Observations

Daily beach surveys during the SandyDuck experiment provided the bathymetry for XBeach and foreshore beach slope in the S2006 parameterizations (Fig. 1). Wave height from the FRF Waverider buoy, located offshore in approximately 17 m water depth, was reverse shoaled to deep water and used as input in the parameterized model (Eqs. 1a, 1b, 1c). Wave spectra collected at the FRF 8-m array (Fig. 1) provided the offshore wave-boundary condition data for XBeach (Fig. 2). Waves measured from a cross-shore array of pressure sensors in 0–5 m water depth, between the shoreline and the 8-m array, (Raubenheimer et al., 2001) were used to evaluate XBeach simulated surf zone wave transformation. A tide gauge located at the end of the FRF pier was used for defining tide levels in XBeach (Fig. 2). Observed tide levels were removed from both the modeled and observed runup in order to focus on the wave driven processes.

Observed runup time series were extracted at six alongshore locations (Fig. 1) from video images (Fig. 3). This analysis produced 50 17-minute runup time series over the study period. Collection times are shown in Fig. 2. Each 17-minute time series was analyzed to extract setup and significant incident and infragravity swash. (See Stockdon et al. (2006) for more detail.)

2.2. Model simulations

Water levels at the shoreline were modeled using XBeach (v18), which solves coupled two-dimensional (2-d), depth-averaged equations for short-wave envelope propagation and flow for varying spectral wave and flow boundary conditions (Roelvink et al., 2009). The low-frequency wave motions interact and evolve to produce both low-frequency and, due to nonlinear behavior, some incident-frequency swash (Fig. 4b). Incident waves are dissipated due to breaking and are expected to vanish when the depth is zero. Sediment transport and morphology changes were not included in the simulations. In our case, the 2-d model spanned 380 m in the alongshore and about 800 m in the cross-shore (Fig. 1). The alongshore resolution was 10 m, and the cross-shore resolution varied from 0.5 m in the swash region to 8 m at the offshore boundary. Bathymetry was derived from daily survey data which were interpolated to the XBeach domain using a smoothing method that adapted to the grid resolution (Plant et al., 2002). Direction-frequency wave spectra from the 8-m array were applied to the offshore boundary of the model domain. Water levels from the tide gauge at the end of the FRF pier were applied uniformly to the offshore boundary. The lateral boundaries of the domain were treated as Neumann or no-gradient boundaries. All Xbeach parameters were set to default values except for the wave breaking parameter γ, which was set to 0.42. Details of model sensitivity to wave breaking parameters are described in Section 4.1.

The XBeach model can also be implemented in a horizontally one-dimensional (1-d) domain (i.e., along a single cross-shore transect) where alongshore uniformity is assumed. The 1-d approach has several advantages, including faster simulation times and reduction of required alongshore bathymetric detail. Because the alongshore components of bathymetry, wave groups, and swash are not fully resolved, it is expected that 1-d simulations will produce different swash levels than the 2-d simulations. When implemented in 1-d, separate XBeach domains were defined along each of the six video-based runup measurement lines, while using the same offshore wave and water level boundary conditions as in the 2-d simulations. The sensitivity of wave runup to the choice of dimensional space used in the model will be evaluated in later sections.

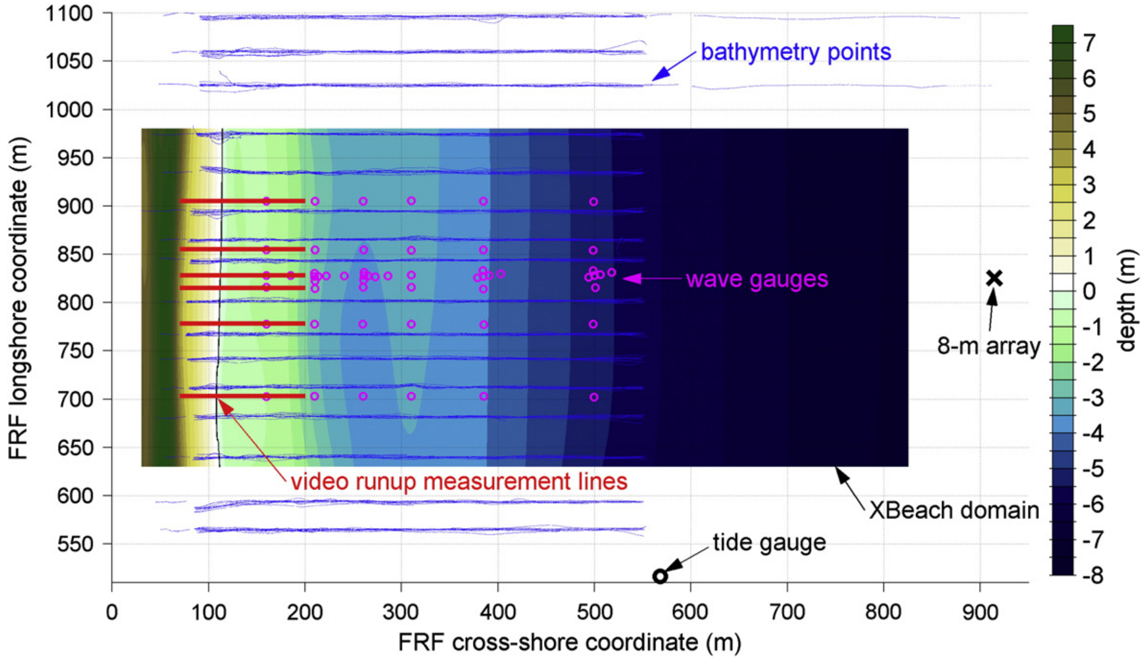

Fig. 1. Nearshore bathymetry (NGVD), measurement locations, and XBeach model domain in the vicinity of the U.S. Army Corps of Engineers Field Research Facility.

2.2.1. Storm scenarios

In addition to using measured wave inputs from the 8-m array, numerical simulations of swash and setup were conducted using hurricane conditions as boundary conditions. To cover a larger range of parameter space, inputs for category 1–5 storm scenarios were extracted from existing simulations that were designed to provide hurricane forcing input to the runup S2006 parameterization (Stockdon et al., 2013). Category 1–5 storms scenarios were constructed by applying hurricane wind speeds and imposing several wind directions to a wave model (Simulating WAves Nearshore (Booij et al., 1999)). The maximum

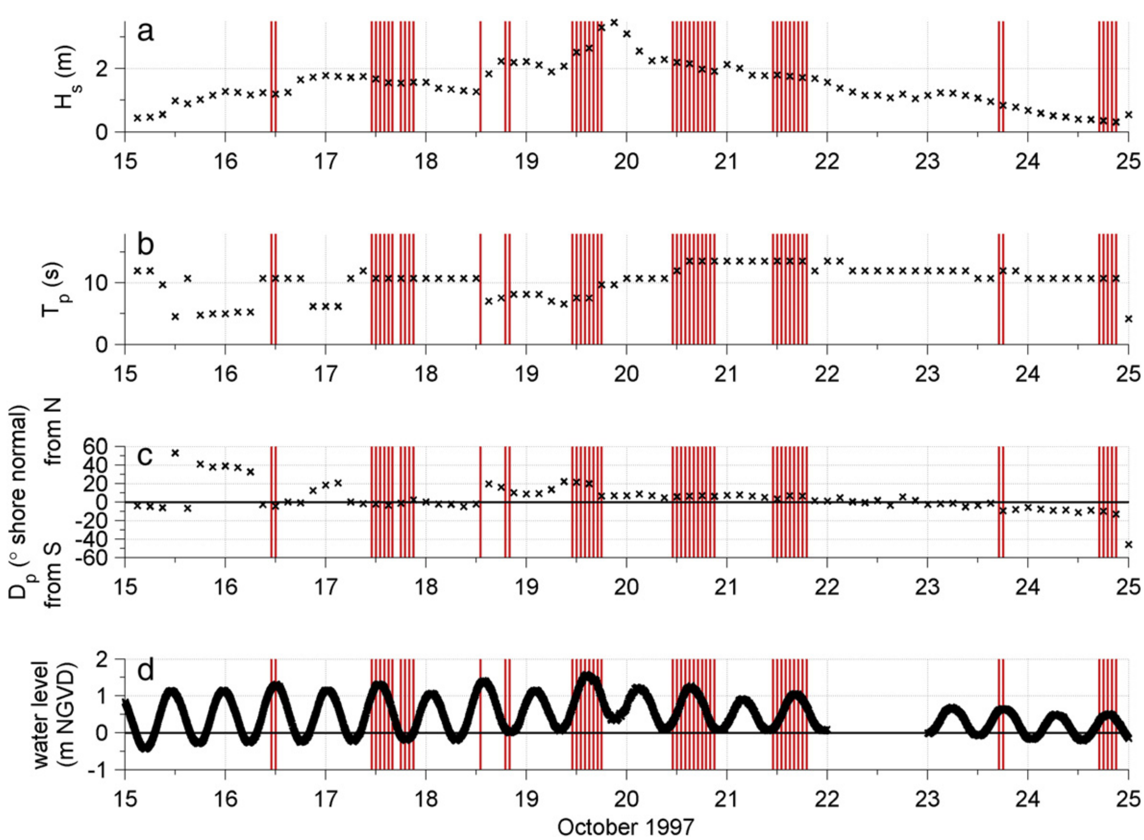

Fig. 2. Observed conditions during the SandyDuck field experiment. Significant wave height (a), peak period (b), and peak direction (c) measured at the FRF 8-m array. Water-levels measured at the end of the FRF pier (d). Vertical lines indicate times of runup observations.

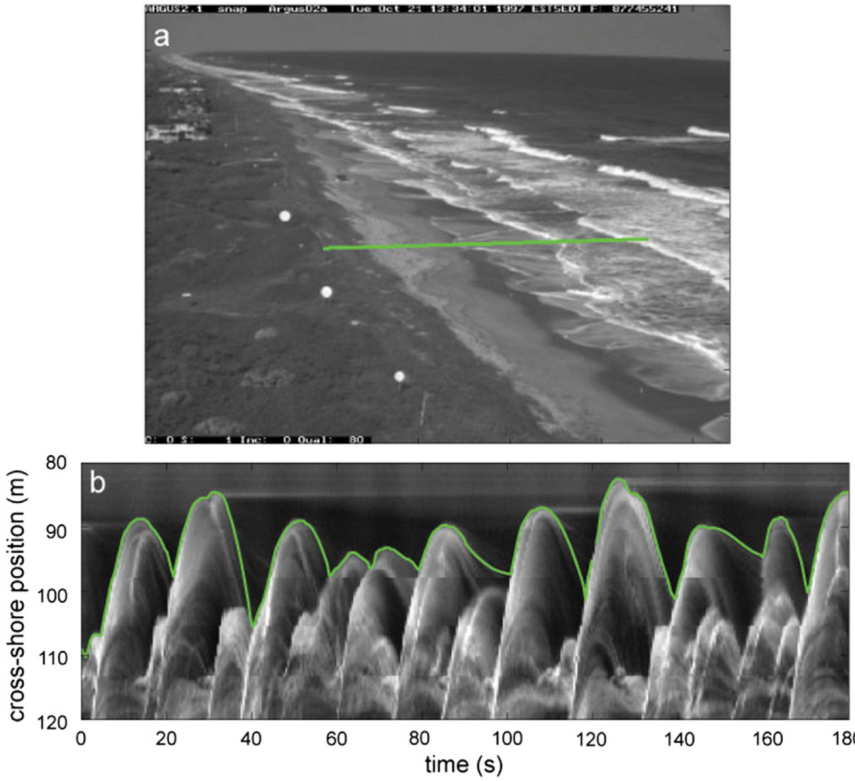

Fig. 3. Camera view from the FRF (a) and corresponding runup timestack (b). The cross-shore transect represents the location of video-derived runup observations. In the timestack of pixel intensity along the transect, each vertical line is the cross-shore variability of intensity at a single time step. The leading edge of swash is digitized through time (green line) and then converted into a time series of water-level elevations. (Modified from Stockdon et al. (2006).).

wave height and corresponding wave period from each hurricane category were used as input at the offshore XBeach boundary in 1-d simulations, which, as will be shown later, have higher accuracy than the 2-d implementation. Similarly, storm-induced water levels for these five scenarios came from SLOSH model simulations (Jelesnianski et al., 1992) as described by Stockdon et al. (2013). The storm scenarios were run in 1-d mode with the offshore boundary extended out to the FRF Waverider buoy, which was moored approximately 3.6 km offshore in 17.4 m of water at the time of the study. This was necessary to adapt to the relatively coarse resolution of the wave and water level inputs, 1.5 km and 0.5–2.0 km, respectively. The bathymetry for these scenarios was a temporal mean of all the 1-d spatially-averaged profiles used in the previously described 1-d simulations. Observations of wave runup do not exist for these conditions, so the accuracy of simulated swash and setup could not be assessed. However, the simulated values were compared to calculations obtained using the runup parameterization (Stockdon et al., 2006) to determine if they were consistent with what would be expected based on observations from a range of sites and conditions.

2.2.2. Extraction of simulated runup

The modeled shoreline water levels can be treated similarly to measurements obtained from video-based observations. The numerically simulated swash location was extracted at each of the six cross-shore profiles by detecting the shoreward-most wet point at a threshold depth δ (here, δ = 10 cm). The sensitivity of swash measurements to choice of δ has been described by others (Holland et al., 1995; Raubenheimer et al., 1995), and we will return to this issue in Section 4. In the 2-d simulations, where runup profile locations did not correspond exactly to model grid lines, simulated water levels were interpolated in space. Swash and setup values from 1-d and 2-d simulations were compared to each other, with observations, and with the S2006 parameterizations.

3. Results

3.1. Wave transformation

The accuracy of the XBeach simulated waves were evaluated using wave observations in the surf zone (for a description see Raubenheimer et al. (2001)). Using the 2-d implementation, the simulated significant wave heights (Fig. 5) compared well to the surf zone observations, with root-mean-square errors (rmse) ranging from 0.21 m at the wave gauges located near x = 500 m (mean depth = 5.3 m) to 0.41 m at the shallowest locations near x = 160 m (mean depth = 1.1 m). The mean difference error ($\mu\Delta$) for the 2-d runs was 0.08 m, indicating a small positive bias in the modeled wave heights. The 1-d implementation produced similar results with rmse ranging from 0.28 m offshore to 0.36 m nearshore and $\mu\Delta$ of −0.04 m.

3.2. Wave setup and swash

XBeach runup simulations of setup, incident swash, and infragravity swash were compared to both video-based observations and predictions using the S2006 parameterization (Fig. 6). The 1-d simulations produced the best predictions of setup with rmse of 0.13 m and a skill (R^2) of 0.68, which is significant at the 95% confidence level. For this and the following analyses, the 95% significance threshold was about 0.02 based on 209 observations. The predictions using S2006, which was based in part on this dataset, had the poorest performance ($\mu\Delta$ = 0.01 m; R^2 = 0.41; rmse = 0.21 m, Table 1), reflecting site-specific uncertainty in the parameterization, which we revisit in Section 4.

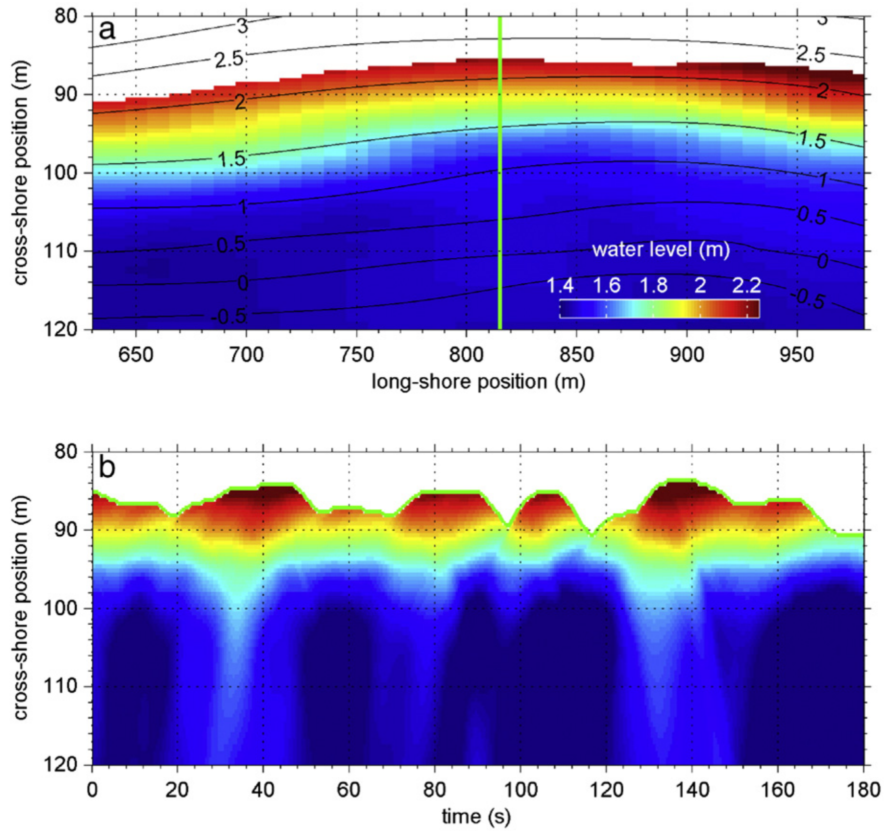

Fig. 4. Plan view showing the spatial variability of XBeach water-level output at one time step Oct 19, 1997 (a). The timestack (b) shows the cross-shore and temporal variation of XBeach water levels at a single longshore location (y = 815 m, green vertical line in a).

Infragravity-band swash predictions varied substantially for the three methods. Based on rmse, the most accurate prediction for S_{ig} was from the S2006 model ($R^2 = 0.54$, rmse = 0.26 m), and the least accurate was from the 2-d implementation of XBeach ($R^2 = 0.59$, rmse = 0.66 m). The large rmse reflects a bias ($\mu\Delta = -61$ cm), indicating an underprediction of observed S_{ig}. The skill of the 1-d XBeach prediction of infragravity-band swash to the observations was also high, but included a regression slope error (b = 0.55, less than an ideal regression slope of 1.0) such that low swash heights were underpredicted and high swash heights were overpredicted (Fig. 6; Table 1).

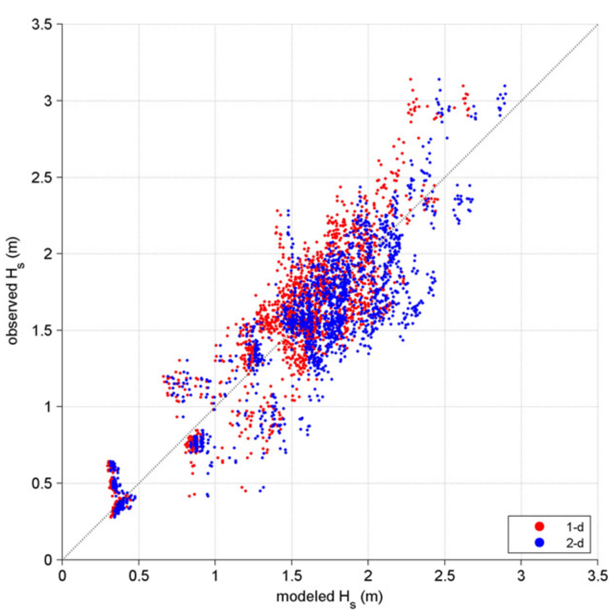

Fig. 5. Comparison of modeled and observed wave height in the surf zone for both the 1- and 2-dimensional XBeach implementations.

The most accurate incident-band swash height predictions were made by the S2006 model, based on high R^2 value and low rmse, 0.42 and 0.36 m, respectively. The S2006 prediction had a higher R^2 than the XBeach predictions but also included a regression slope error such that low swash heights were underestimated and high swash heights were overestimated. Because of short-wave averaging in the modeled processes, XBeach simulations underpredicted incident-band swash heights, had low R^2 values (0.14 and 0.12 for 1-d and 2-d, respectively), and high rmse (0.57 m and 0.82 m for 1-d and 2-d, respectively). It is clear from the scatter in the model predictions that XBeach modeled incident-band swash does not offer an improvement over predicting the mean value (about 1 m). The 1-d model offered only a minor improvement over the 2-d model.

3.3. Simulations of hurricane scenarios

Because the simulations during hurricane conditions could not be compared to observations, these results were compared to the predictions made using the S2006 parameterization. Previously presented comparisons show the extent to which XBeach simulations can be used as surrogates for actual runup (setup and swash) observations for the purpose of extending the parameterizations to extreme storm conditions (Table 1). Using hurricane forcing as input, XBeach-modeled setup for category 1 conditions lay near 1:1 trend line (Fig. 7a), indicating that XBeach and S2006 produced nearly the same result under these conditions. However, as storm intensity grew, and

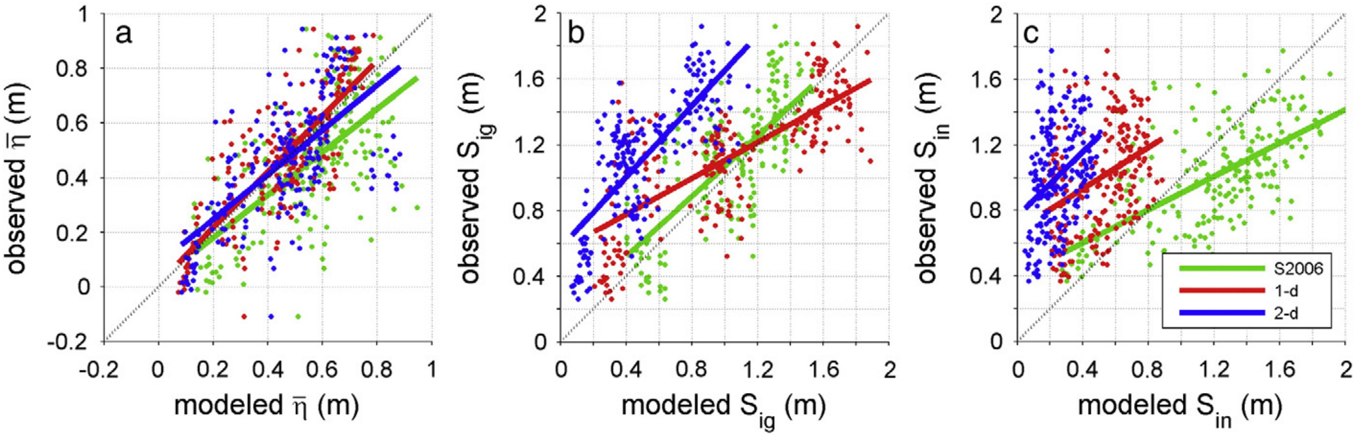

Fig. 6. Observed and modeled setup (a), infragravity swash (b), and incident swash (c). The S2006, 1-d XBeach, and 2-d XBeach models are represented by green, red, and blue dots, respectively. Solid lines indicate linear-regressions fitting the model results to the data.

waves and surge interacted with the upper beach and/or dune face, XBeach modeled setup increased more than was predicted by the S2006 parameterization. If these XBeach results during storm conditions can be verified using field observations, particularly when waves are interacting with the dune, then the model simulations could be useful in modifying the parameterized range of the S2006 model. For infragravity swash, differences between 1-d XBeach simulations and S2006 were about the same as differences between observations and S2006 (Table 2). XBeach values for hurricane conditions are lower expected from simply extrapolating the 1-d model results from non-hurricane conditions (Fig. 7b). The mean and rmse differences between the 1-d hurricane results and the S2006 model are very similar to the differences between S2006 and the observations, suggesting that both models are equally valid (Table 2). Thus, XBeach can be used to extend the S2006 parameterization for infragravity swash during storms. As expected, XBeach-simulated S_{in} during hurricane conditions was substantially smaller than that predicted using S2006 (Fig. 7c). When evaluating whether XBeach can be used to simulate swash during hurricane conditions, it is important to note that swash processes under highly dissipative conditions, such as during storms, are typically dominated by infragravity energy (Thornton and Guza, 1982). As such, an underestimate of incident band swash in XBeach will have a relatively small influence on the total swash magnitude during hurricane conditions.

Table 1
Statistics describing the fit between observations and parameterized, numerical, and assimilated results (Figs. 6 and 11). Prediction errors for setup ($\bar{\eta}$), infragravity swash (S_{ig}), and incident swash (S_{in}) include the mean difference ($\mu\Delta$), root-mean-square error (rmse), skill (R^2), and slope (b) of best-fit linear regression. The rsme for assimilation results using the uncorrected XBeach model are shown in parentheses.

Parameter	Model	$\mu\Delta$ (m)	rmse (m)	R^2	b
$\bar{\eta}$	S2006	0.10	0.21	0.41	0.78
	1-d Xbeach	−0.02	0.13	0.68	1.02
	2-d Xbeach	0.00	0.17	0.46	0.82
	Assimilation	0.05	0.16 (0.16)	0.91	1.13
S_{ig}	S2006	−0.06	0.26	0.54	0.91
	1-d Xbeach	−0.09	0.35	0.55	0.55
	2-d Xbeach	−0.61	0.66	0.59	1.08
	Assimilation	−0.03	0.23 (0.42)	0.96	1.04
S_{in}	S2006	0.19	0.36	0.42	0.51
	1-d Xbeach	−0.49	0.57	0.14	0.63
	2-d Xbeach	−0.76	0.82	0.12	0.98
	Assimilation	0.28	0.28 (0.32)	0.94	0.71

4. Discussion

The analysis and results presented here relied on making a number of assumptions, many of which were contained in model-parameter choices that gave the best comparisons of the XBeach model to the observational data. The danger of using numerical models is that the results may depend on poorly constrained coefficients. For instance, Apotsos et al. (2008) showed that the best parameter values for predicted wave-heights varied with external conditions that changed from one field experiment to another and even changed within a single field experiment as the boundary conditions changed. This effect has been noted elsewhere (Plant et al., 2011; Ruessink et al., 2003). Site-specific sensitivity to model parameter choice also affects the S2006 model. Stockdon et al. (2006) showed that the model coefficients that best fit all the data resulted in systematic prediction errors for individual data sets, including the 1997 SandyDuck data set used here (e.g., Fig. 6c, which exhibits a slope error). Similarly, XBeach is vulnerable to prediction errors due to sensitivity to adjustable model coefficients.

4.1. XBeach parameter sensitivity

Energy dissipation due to depth-induced wave breaking of the incident band waves in XBeach is modeled as a dissipation rate times a probability of wave breaking (Roelvink, 1993). This wave-breaking formulation includes two free parameters; one that controls the magnitude of the dissipation rate, α, and the other dictates the fraction of breaking waves as a function of the wave height to water depth ratio, γ. The first parameter, α, is typically set at 1.0 (Battjes and Janssen, 1978; Roelvink, 1993; Roelvink and Brøker, 1993). Sensitivity to this parameter was not explored here. The default value for γ is 0.55 and is based on a limited number of tests, primarily laboratory. Comparisons between field observations and model predictions of wave height show large variation in the optimal value of γ depending on both the wave conditions and the empirical relationship chosen for γ (Apotsos et al., 2008).

Using the 1-d XBeach domains for all runup observation times, we explored the sensitivity of modeled wave heights, setup, and swash to the choice of γ (Fig. 8; wave height comparisons are not shown). In addition to the default value for γ, 0.32 and 0.42 were tested. These values are consistent with field observations of wave height to water depth ratios observed at the field site in Duck (Guza and Thornton, 1981; Sallenger and Holman, 1985). For $\bar{\eta}$ and S_{ig}, the value of $\gamma = 0.42$ provided the best fit with the observations, as indicated by lower mean and rmse differences (Fig. 8). In an additional sensitivity test, XBeach was implemented using an advective-deterministic breaking formulation

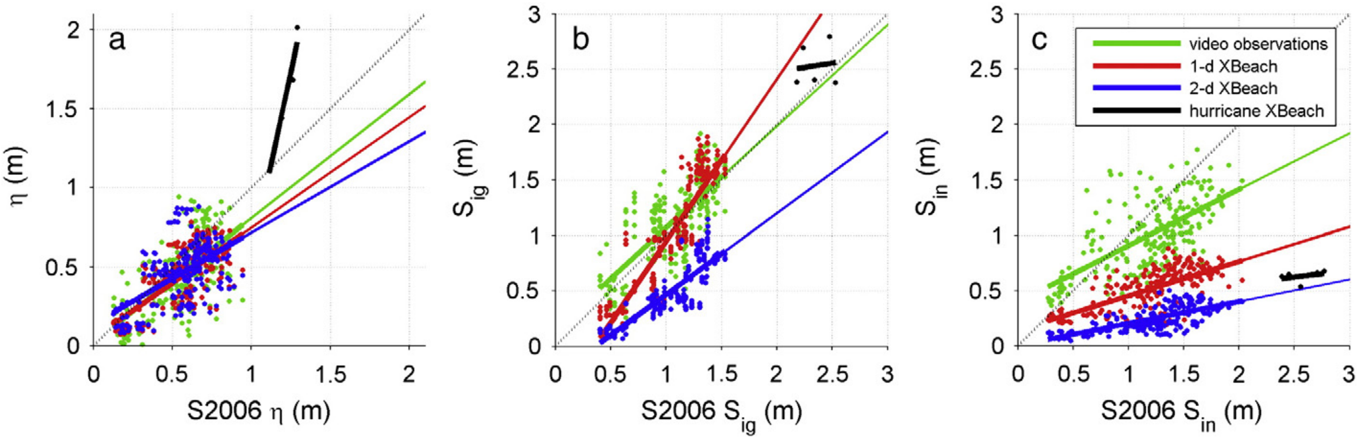

Fig. 7. Observations and XBeach simulations of setup (a), infragravity swash (b), and incident swash (c) compared to values parameterized using the S2006 model. Comparisons to video-based observations are shown in green. Comparisons to 1-d XBeach, 2-d XBeach, and XBeach during hurricane conditions are represented by the red, blue, and black dots, respectively. Solid lines indicate linear regressions between the parameterized results and the Xbeach and observational data.

(Daly et al., 2012), where wave breaking is turned on and off using upper and lower values of γ, in this case 0.52 and 0.30, respectively. Comparison of 1-d model results to the observed data indicated that this formulation did not offer an improvement over the static breaking formulation using $\gamma = 0.42$ (Fig. 8).

4.2. Comparison between 1-d and 2-d XBeach simulations

Estimates of infragravity and incident band significant swash differed between the 1-d and 2-d XBeach implementations. The 2-d implementation produced S_{ig} that was consistently too low as compared to the observations (Fig. 6). The 1-d implementation included both under and over prediction of S_{ig}, as indicated by the large slope error ($b = 0.5$). Model performance for the 1-d implementation was best during shore-normal wave conditions. When the wave approach was $\pm 15^{\circ}$ from shore-normal (approximately ~80% of the cases), the mean error in 1-d modeled S_{ig} was 0.02 m compared to −0.56 m when waves were oblique to the shoreline. However, the errors in S_{ig} for the 2-d implementation were high regardless of wave approach: −0.59 m and −0.71 m for shore-normal and oblique waves, respectively. Results from a particular case with 3-m high waves, and a shore-normal approach, illustrate the most extreme differences in the different spatial implementations (Fig. 9a). The 1-d case produced very high runup maxima, while the 2-d case exhibited lower runup maxima but also lower minima. The distribution (Fig. 9b) of 1-d water level elevations were positively skewed (0.22), while the 2-d water level elevations were negatively skewed (−0.30). The observed water level distributions had a skewness of −0.05. The frequency spectra of water levels (Fig. 9c) indicated that the swash elevation spectra were broader banded in the 1-d case compared to the 2-d case.

Differences in swash heights between 1- and 2-d runs may result if cross-shore evolution of wave heights differs between the two simulation approaches or if alongshore interactions dissipate swash differently through frictional or nonlinear processes (Cox et al., 2013; Guza and Feddersen, 2012; Reniers et al., 2006, 2010). In this case, there were no substantial differences in the wave height modeling across the surf zone between the two implementations (Fig. 5). A preliminary analysis of the effects of longshore currents on swash magnitude variations between 1- and 2-d implementations was inconclusive. Cross-spectral analysis of modeled shoreline and surf zone water level time series began to reveal differences between 1- and 2-d swash modeling. The analysis showed standing-wave motions in the infragravity frequencies and strong reflection and resonance in the 1-d domain, likely associated with the increased swash variance or magnitudes. Coherence between the swash and surf zone water levels was lower in the 2-d model implementation, possibly suggesting that alongshore dissipation and/or nonlinear interactions in the swash zone may be decreasing water level amplitudes. Additional investigations, which are outside the scope of this study, are required for a complete understanding of the swash differences between the two spatial implementations.

Table 2
Statistics describing the fit between S2006 parameterizations and data/simulations (Fig. 7). Prediction errors for setup ($\overline{\eta}$), infragravity swash (S_{ig}), and incident swash (S_{in}) include the mean difference ($\mu\Delta$), root-mean-square error (rmse), skill (R^2), and slope (b) of best-fit linear regression.

Parameter	Data/simulations	$\mu\Delta$ (m)	rmse (m)	R^2	b
$\overline{\eta}$	Video	0.10	0.21	0.41	0.78
	1-d	0.12	0.19	0.49	0.70
	2-d	0.10	0.20	0.32	0.58
	1-d hurricane	−0.30	0.39	0.96	4.65
S_{ig}	Video	−0.06	0.26	0.54	0.91
	1-d	0.03	0.28	0.77	1.46
	2-d	0.55	0.57	0.69	0.73
	1-d hurricane	−0.18	0.27	0.01	0.16
S_{in}	Video	0.19	0.36	0.42	0.51
	1-d	0.68	0.75	0.44	0.31
	2-d	0.95	1.01	0.50	0.20
	1-d hurricane	1.94	1.95	0.12	0.12

4.3. Runup sensor depth choice

The choice of threshold depth, δ, used to extract shoreline water levels (runup) from the XBeach model affected the estimates of setup and swash. Runup was extracted from all of the XBeach simulations using different values of δ, analogous to previous tests of runup sensitivity to the height of runup wires used in field experiments (Holland et al., 1995). Setup elevation decreased more-or-less linearly with increasing δ, with about a 2-cm loss in setup elevation for each 1-cm increase in δ (Fig. 10). The sensitivity of setup to δ did not differ substantially between the 1-d and 2-d implementations of XBeach. Analysis of the sensitivity of field observations documents a similar dependence: increasing δ results in a loss in setup magnitude, ranging between about 0.5 and 1.0 cm (Holland et al., 1995). In the XBeach simulations, significant swash was not as sensitive to δ. Swash gradually increased as δ increased, with a maximum swash height occurring at $\delta = 5$ cm. Swash then decreased slightly with further increases in δ (Fig. 10).

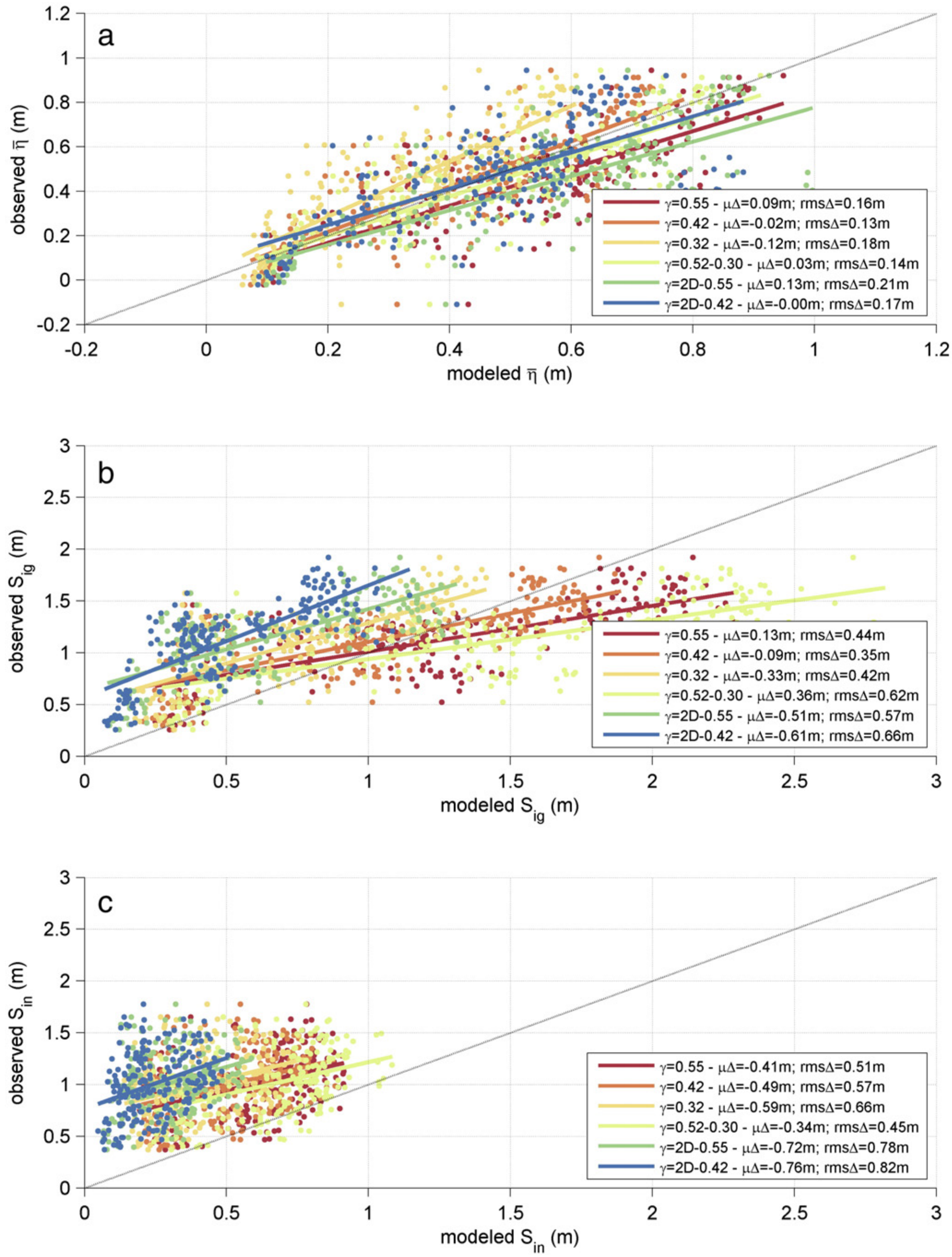

Fig. 8. Sensitivity of setup and swash predictions to variation in the breaking parameter (γ) at six locations across the surf zone. The default formulation was used except for the case where $\gamma = 0.52$–0.30, indicating that the Daly et al. (2012) formulation was used.

4.4. Improved parameterization utilizing XBeach output

Our analysis tested the accuracy of XBeach model predictions of setup and swash and systematic errors in both the 1-d and 2-d implementations. Systematic errors are also present in the S2006 parameterization. For example, at the Duck field site alone, rmse for the S2006 runup parameterization varied between 34 to 69 cm, depending on the specific field experiment (Stockdon et al., 2006). The S2006 parameterization omits many surf zone process details, including alongshore and cross-shore variability of the shoreline and sandbars. It has been shown in simulated tests that some infragravity swash variation can be explained by including additional bathymetric details (Cox et al., 2013). It is possible to combine the observation-based parameterization and the numerical model results in a way that results in less overall error than using one model alone.

If the prediction errors from the different modeling approaches are not correlated to each other, then the results from XBeach (1-d and/or 2-d) and S2006 can be combined to reduce the total error by exploiting advantages of each approach. Because the S2006 parameterization provides a good fit to a broad range of conditions, we use it as a prior condition that can be updated through assimilation of the XBeach simulations.

$$S_{\text{assim}} = S_{\text{param}} + w\left(S'_{\text{XBeach}} - S_{\text{param}}\right), \tag{2a}$$

where S_{assim} is the assimilated value, S'_{XBeach} is the XBeach prediction, and S_{param} is the value based on the S2006 parameterization for either setup, incident swash, or infragravity swash. Bias and gain (the regression slope error) corrections have been applied to XBeach values, as

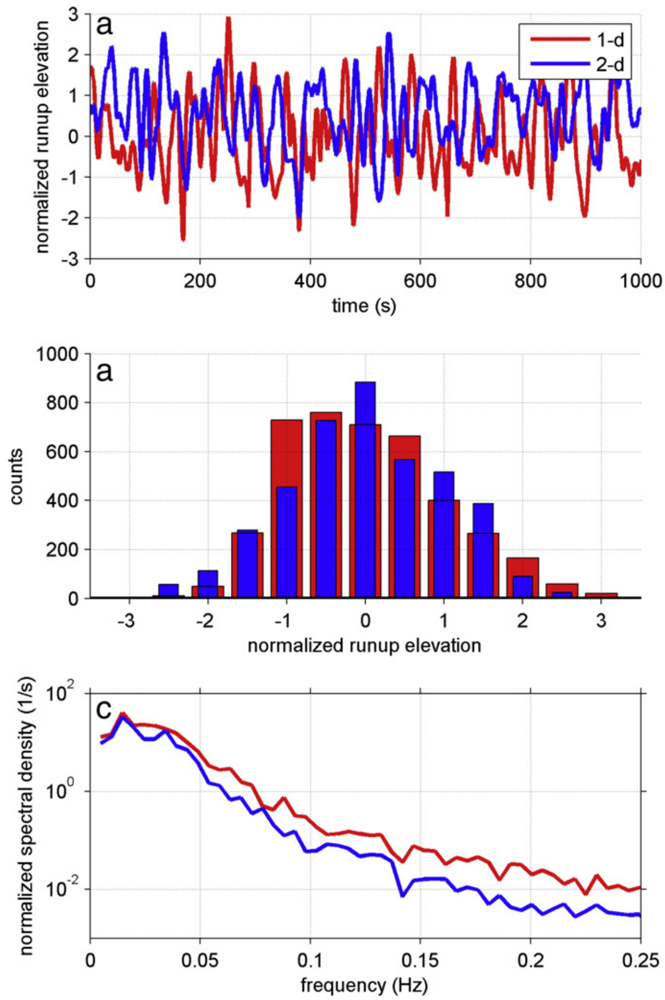

Fig. 9. Sample runup time series (a), histograms (b), and spectra (c) from the 1-d (red) and 2-d (blue) Xbeach simulations. Time series were normalized to have zero mean and unit variance.

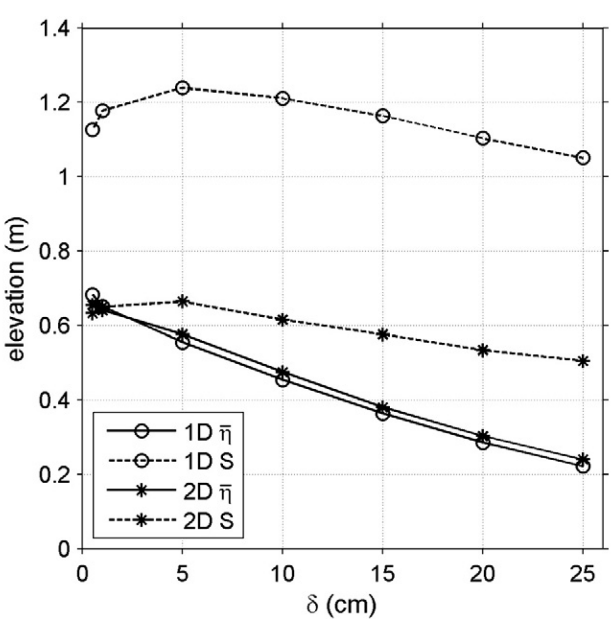

Fig. 10. Sensitivity of setup (solid lines) and swash (dashed lines) to threshold depth (δ) used to extract runup from 1-d (circles) and 2-d (squares) XBeach simulations.

indicated by the prime notation, to ensure that systematic errors are not reintroduced to the assimilation. The weighting factor, w, is a function of the expected errors of both the S2006 and the XBeach simulations:

$$w = e_{\text{param}} / \left(e_{\text{param}} + e'_{\text{XBeach}} \right), \tag{2b}$$

where e_{param} is the variance of the S2006 prediction errors and e'_{XBeach} is the variance of the XBeach prediction errors. The error terms are estimates based on prior experience, such as from the results presented in Table 1. In this formulation, if the errors of the XBeach model are very small compared to the S2006 model, the value for w approaches 1, and the assimilated result is equal to the XBeach prediction. Conversely, if the XBeach errors are relatively large, the weight approaches 0, and the assimilated result returns the S2006 prediction.

Using the 1-d XBeach implementation, assimilated setup and infragravity and incident swash yielded errors (rmse) that were either the same as or smaller than the individual model inputs (Table 1). For instance, the assimilation of XBeach and parameterized predictions for setup yielded errors that were equal to the XBeach errors, even though the errors in S2006 alone were higher. The systematic over-prediction of setup by the S2006 model (Fig. 11a) was reduced by giving higher weight to the XBeach model. The roles were reversed for infragravity swash. The S2006 model was more accurate than XBeach, and the assimilation provided an improvement by (1) correcting the XBeach bias and gain and (2) canceling errors in the cases where one model overpredicted and the other underpredicted the swash height. In the case of the incident swash, the XBeach model severely underpredicted the observations, and higher weight was given to the S2006 model. The value of including the XBeach incident swash in the assimilation was to reduce scatter (Table 1).

Overall, the assimilation results reduced the predicted error variance (total rmse = 0.40 m) by 19% compared to the S2006 parameterization (total rmse = 0.49 m) and by 63% compared to the XBeach result (total rmse = 1.07 m). The assimilation weights were, on average, 0.5 indicating that XBeach and S2006 contributed equally to the assimilation. Additionally, the assimilation result was not overly sensitive to the precise value of the assimilation weights. For instance, the results changed little if $w = 0.5$ was used in all cases (i.e., an average of XBeach and S2006 output), rather than allowing the weight to vary for setup and swash components. Thus, prior knowledge of the prediction errors, which determine the weights, need not be perfect. Furthermore, the assimilation results were similar for setup and incident swash if the XBeach model was not corrected for systematic errors (e.g., gain and bias errors, Table 1). Correction of the systematic bias associated with the 2-d XBeach simulations of infragravity swash improved the assimilation results in this case (Table 1). Thus, XBeach simulations, corrected for bias if possible, can be used to correct the S2006 parameterization by either (1) updating the S2006 parameters to fit these additional data or (2) assimilating the two, as we have done here.

5. Conclusions

Runup and its components, setup and swash, can be predicted from a parameterized model that was developed by comparing observations of runup to offshore wave height, wave period, and local beach slope (Stockdon et al., 2006). This parameterization can suffer from systematic errors due to site-specific characteristics that were not included in the model. Additionally, parameterization skill is unknown under extreme conditions where observations are lacking. To address the parameterization deficiencies, numerical models can be used to simulate the storm-driven runup to improve and extend the parameterized approach.

Runup was numerically simulated using XBeach and compared to observations to investigate the simulation accuracy. XBeach simulated runup was also compared to the S2006 parameterization to determine

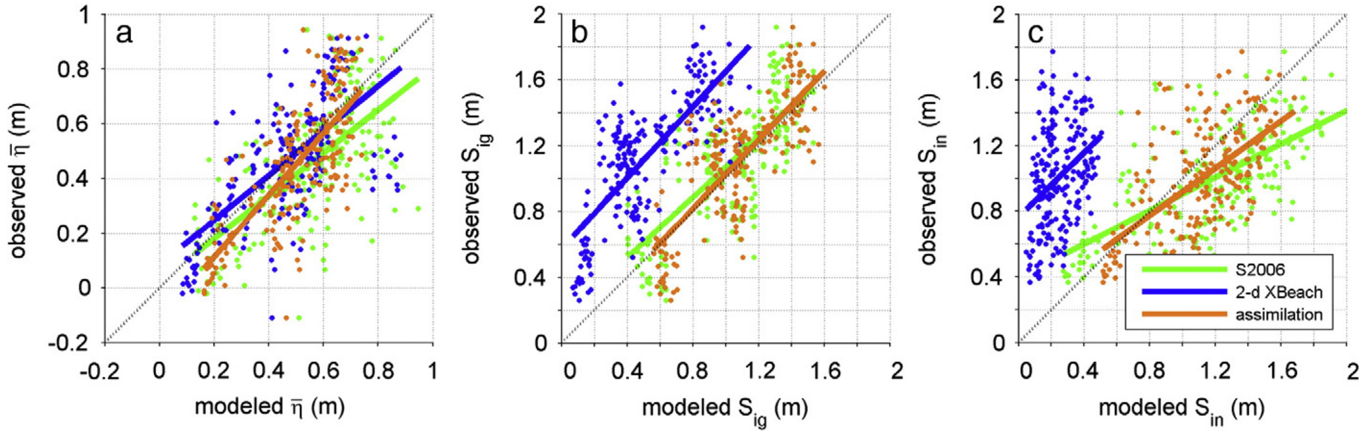

Fig. 11. Comparison of observed setup (a), infragravity swash (b), and incident swash (c) to that modeled using S2006, Xbeach, and an assimilated version of the two. Statistics are presented in Table 1.

if predictions from the two are consistent. The analyses demonstrated that setup was accurately predicted by both the numerical simulations and parameterized model. Infragravity swash was most accurately predicted by the parameterized model. The numerical model predictions of infragravity swash suffered from substantial bias or gain errors that were dependent on whether a 1-d or 2-d spatial domain was used. Nonetheless, all of the predictions of infragravity swash were well correlated to the observations if these systematic errors were corrected. The numerical simulations did not resolve the incident swash motions, as expected, and the S2006 model performed best at predicting incident swash heights. With the systematic errors corrected, an assimilated prediction using a weighted average of the S2006 model and the numerical simulations resulted in an error reduction of 19% compared to the parameterization and of 63% compared to XBeach.

XBeach simulations of hurricane wave conditions were used to test the parameterized runup to storm conditions that have not been previously observed. The extreme-storm simulations produced infragravity swash results that were consistent with the observationally constrained simulations of swash. The simulations of setup under extreme conditions were consistent with the parameterized estimates under the category-1 case, but for more extreme storms, simulated setup was higher than predicted by the S2006 model. These results suggest that numerically simulated runup, with bias and gain errors corrected, may be used to modify or expand field-based parameterizations of setup and swash to more energetic storm conditions that have not been previously observed.

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