11TH International Workshop on Wave Hindcasting and Forecasting & 2nd Coastal Hazards Symposium; Halifax, Nova Scotia, Canada; October 18-23, 2009

COASTAL WAVE ENERGY DISSIPATION: OBSERVATIONS AND STWAVE-FP PERFORMANCE

Jeffrey L. Hanson
US Army Corps of Engineers Field Research Facility
1261 Duck Rd; Kitty Hawk, North Carolina 27949; USA
Email: Jeffrey.L.Hanson@usace.army.mil

Harry C. Friebel,
US Army Corps of Engineers - NAP, Philadelphia, Pennsylvania, USA

Kent K. Hathaway
US Army Corps of Engineers Field Research Facility, Duck, North Carolina, USA

1. INTRODUCTION

A significant challenge to numerical wave modeling is capturing the dynamics of wave transformation in coastal waters. Interaction with the bottom becomes significant at water depths less than one-half the wavelength ($d<L/2$). Bottom interactions modify the wave energy balance through shoaling, refraction, and bottom friction. Furthermore, shoaling leads to additional dissipation due to depth-induced breaking. It is generally accepted that dissipation processes are the least well-represented in numerical wave models (Cavaleri et al., 2007). Adding to the complexity of this environment is increased wave non-linearity; as waves enter very shallow water, frequency dispersion diminishes and resonant interactions dominate (Holthuijsen, 2007). Careful measurements of wave transformation processes in the coastal environment are required to fully support the continued advancement of improved model physics.

Here we report on progress in quantifying the performance of the Steady-state spectral WAVE model - Full Plane version, or STWAVE-FP (Smith, 2007), in a high-energy coastal environment. Validation data are obtained from a new cross-shore wave and current array located at the US Army Corps of Engineers Field Research Facility (USACE-FRF) in Duck, North Carolina. Coupled with National Data Buoy Center (NDBC) Virginia Beach Station 44014, the array captures wave evolution over the continental shelf leading up to the outer surf zone. A high spatial resolution (25-m) STWAVE-FP modeling domain with comprehensive model validation tools (Hanson et al., 2009) transform this site into a unique coastal wave modeling test bed. Here we use observation and modeling results to examine the bottom friction source term in STWAVE-FP, which has been modified from Holthuijsen (2007) to include a manning's roughness coefficient (Smith, 2007). The results help identify strengths and weaknesses of STWAVE-FP in a dynamic sandy coast environment and provide guidance for future research activities.

2. CROSS-SHORE WAVE AND CURRENT ARRAY

To collect essential data required for an improved understanding of coastal wave transformation, and facilitate development of the next generation coastal numerical wave models, the US Army Corps of Engineers has deployed a cross-shore wave and current array in the energetic shelf environment off Duck, North Carolina. As depicted in Figure 1, the array consists of 4 bottom-mounted Nortek Acoustic Wave and Current (AWAC) sensors at depths of 5, 6.5, 8.5 and 11.2-m and two Datawell Directional Waverider buoys at 17 and 26-m depths. An instrument tower at the end of the FRF pier (8-m water depth) includes a meteorological station with a marine anemometer (RM Young Model 09101) located at an elevation of 19.5 m. The wave stations are in a direct line with a 3-m discus buoy (National Data Buoy Center station 44014) that includes a meteorological station and directional wave sensor at 48-m depth[1]. The array spans 95-km cross-shelf and captures all phases of wave transformation from the outer continental shelf to within the surf zone. Furthermore, a nearshore portion of the array is within field of view of a 43-m high Argus video station providing high-resolution digital color images of surf zone behavior. A profile view of the nearshore (AWAC) portion of the array appears in Figure 2.

[1]The NDBC station 44014 homepage is at http://www.ndbc.noaa.gov/station_page.php?station=44014

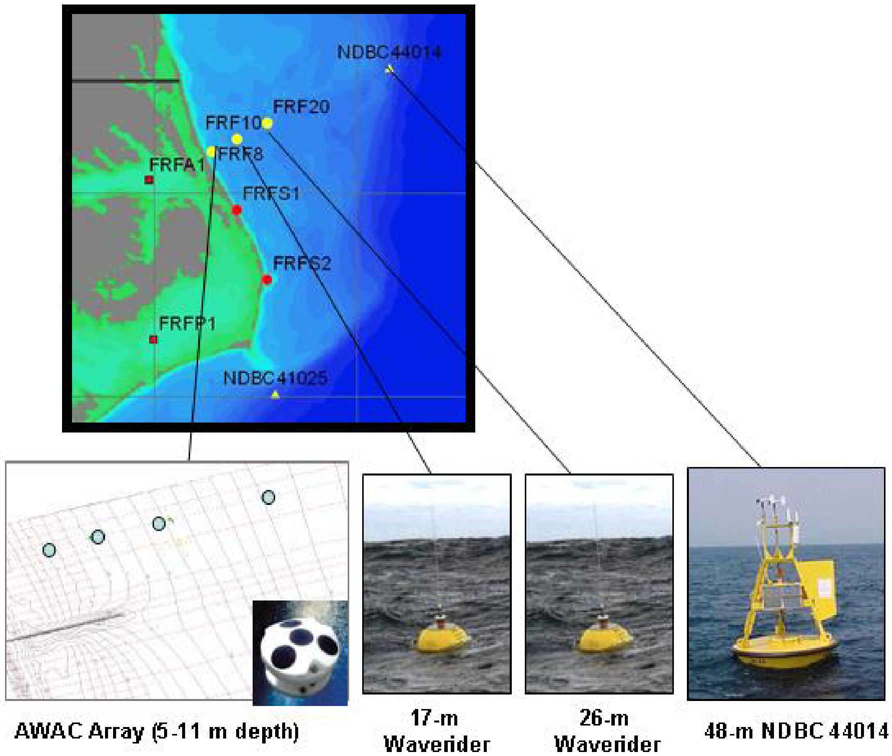

Figure 1. FRF cross-shore wave and current array off Duck, North Carolina.

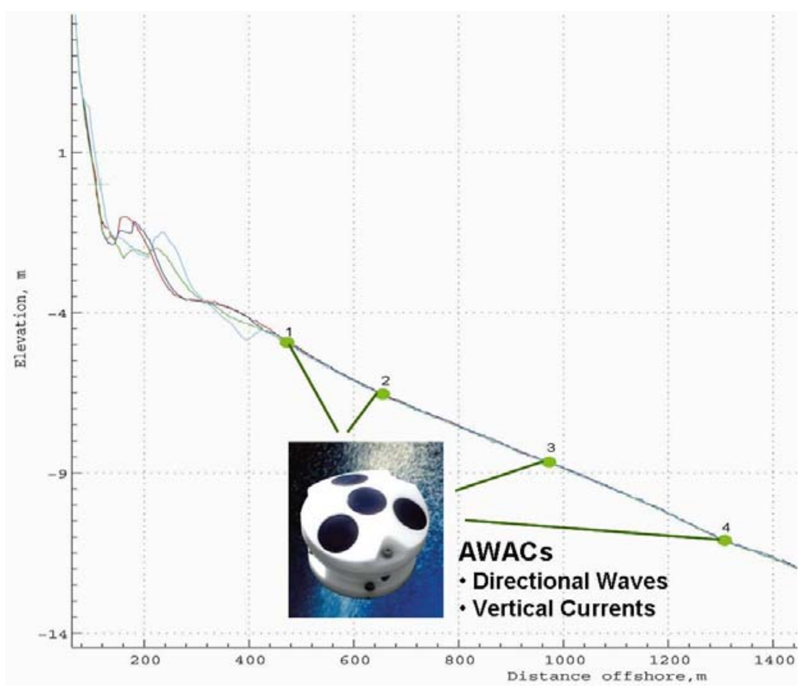

Figure 2. Cross-shore bathymetry showing AWAC sensor placement (relative to NAVD88 water level elevations).

With the exception of on-board buoy processing of spectral coefficients, all of the wave data processing is done by the FRF. The AWAC cross-shore array is cabled to shore via the USACE-FRF pier for real-time data collection and powering the instruments. The array has been in operation since December 2007, initially using Nortek real-time Windows-based software. In June 2008 the collections were switched to in-house developed programs on a Linux platform. Wave data are collected hourly in 34-minute records at a 2 Hz sampling rate. Spectra are computed with the Iterative Maximum Likelihood Method (IMLM). Data from the 17-m Waverider is radio-telemetered to shore on a continuous basis. Spectral coefficients are computed onboard the buoy using the Fourier coefficient method (Longuet-Higgins et al., 1963) from contiguous 30-minute records sampled at 1.28 Hz. The IMLM method is used to convert these to directional wave spectra. Data from the 26-m Waverider are transmitted via Iridium satellite service and operated by the Coastal Data and Information Program (CDIP). Half-hourly spectral coefficients are provided by CDIP. The MLM method is used to convert these to directional wave spectra as well. All resulting spectra are passed to the FRF wavefield analysis system (Hanson, 2001) which provides a variety of real-time displays and archives the data into monthly files for each station.

3. OBSERVATIONS

A goal for this study is to describe bottom friction across the shelf, up to the point of depth breaking, and to select an optimum manning's roughness coefficient (n) for the Duck location. To isolate bottom effects in wave evolution, a variety of 'pure' swell events were selected as ground truth in testing the STWAVE-FP bottom friction source term at Duck. The use of pure swell allows us to rule out wind sea growth and whitecapping as factors that contribute to changes in total wave energy across the array. This section provides a description of the selected events.

Swell Events

A data mining tool was developed to search through our archive of monthly wave records to isolate events with the following characteristics:

- Wind speed < 10 m/s
- Wind direction offshore
- Significant wave height > 1 m
- Peak period > 9 s
- Event duration > 6 h

The above process produced several candidate events. To further narrow the selections into a reasonable subset, the corresponding wave spectra and webcam images were carefully examined to isolate events that were reasonably steady over the time period and contained no evidence of wind interaction. After these selections were made, Hurricane Bill occurred off the US east coast in August 2009, providing an additional data set of very long period, large amplitude swells.

The basic characteristics of the four selected swell events appear in Table 1. The significant wave height (H_s) and peak period (T_p) values are computed means for the entire time period at the 17-m station. Event 1 represents a falling swell from a moderate nor'easter of relatively short duration. Winds briefly peaked at 17 m/s on 25 September 2008. As the event moved offshore a series of reasonably young 10-s period swell with wave heights just below 2-m were observed. Event 2 also represents falling swell from a nor'easter, but of much longer duration. The storm developed in the region on 19 October with peak sustained winds >16 m/s lasting for 21 h. Swells of about 14-s wave period and 2.3-m height were observed as the storm receded. Event 3 represents swell from a more distant offshore storm. This event brought fairly low-period waves of nearly 15-s with an average wave height of 1.4 m. Event 4 was a very low period (18-20s), high amplitude (H_s ~ 3 m) swell produced by Hurricane Bill as it headed north approximately 660 km east of Duck as a category 2 storm.

Images from the FRF Argus video system were inspected to ensure that the selected events were devoid of windsea growth and whitecapping. A snapshot of the wavefield including the surf zone from each event appears in Figure 3. The images show that Events 1 and 2 were fairly short-crested wave events, characteristic of locally-generated (young) swell. In contrast, the wavefields associated with Events 3 and 4 were long crested and representative of mature swell. In particular, swell from Hurricane Bill (Event 4) produced a notably wide, active surf zone along the coast.

Table 1. Selected Swell Events for STWAVE Bottom Friction Study

Event	Date	Hs (m)	Tp (s)	Comments
1	27-28 SEP 2008	1.7	10.4	Nor'easter – short duration
2	20-21 OCT 2008	2.3	14.3	Nor'easter – long duration
3	19 FEB 2009	1.4	14.8	Distant storm
4	22 AUG 2009	3.1	18.0	Hurricane Bill

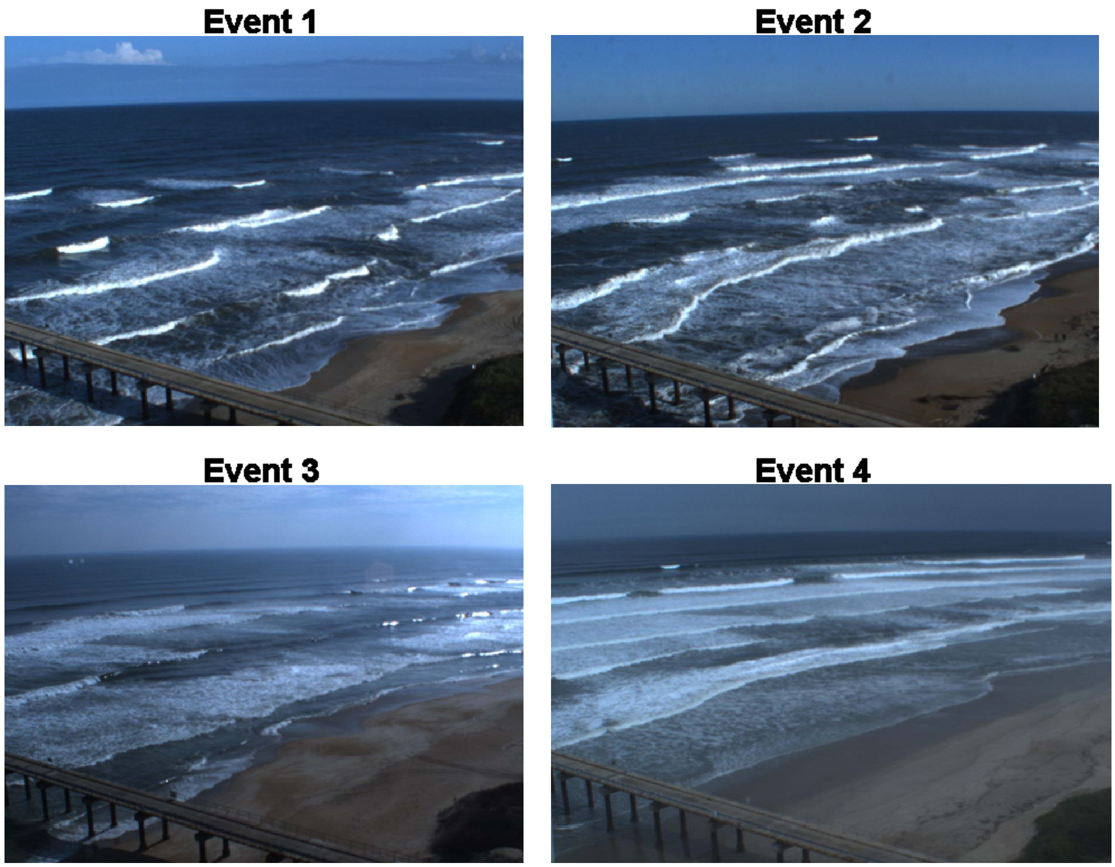

Figure 3. Swell event webcam snapshots from FRF observation tower.

Cross-Shore Wave Evolution

We use Event 4 (Hurricane Bill) to demonstrate cross-shore measurement fidelity and characterize swell transformation as it moves into shallow water. Sample cross-shore data from Event 4 appears in Figure 4. The evolution of H_s at each station over the life of the event is depicted in Figure 4a. The effect of wave shoaling can be observed early in the record (10:00 – 17:00 on 22 Aug) as the inner 5- and 6-m stations have the highest wave heights. Near the peak of the event, when we most certainly had wave breaking over the inner stations, the influence of wave dissipation processes are evident as wave heights evolved from nearly 4-m at the outer 26- and 17-m stations to less than 3-m at the inner station. Figure 4b depicts the energy-frequency spectra at each station across the array during the peak of the swell event (see vertical reference line on Figure 4a). Evidence of wave nonlinearity appears as harmonic sub-peaks down-shifted from the dominant peak. These harmonics are likely a result of triad resonant interactions in shallow water (Holthuijsen, 2007), and are characterized by waveforms that substantially deviate from sinusoidal shapes.

The transformation of wave energy across the shelf during the peak of Hurricane Bill (Event 4) is represented by Figure 4c. The fraction of incoming wave energy, represented by the ratio of total energy at each station to total energy at the outer (26-m) station, is presented as a function of station depth. These observations show three different wave transformation zones. Starting with the outer 26-m station and working shoreward, Zone A (Figure 4c) represents a net energy loss by bottom friction and refraction, Zone B represents energy gain through wave shoaling, and finally Zone C represents energy loss by depth-induced breaking. As linear wave theory dictates, the existence and extent of these zones are a strong function of the incoming wave properties. For example, when the shallow water breaker index H/d does not reach the breaking threshold of approximately 0.78, Zone C is absent and the waves continue to shoal all the way up to the 5-m station.

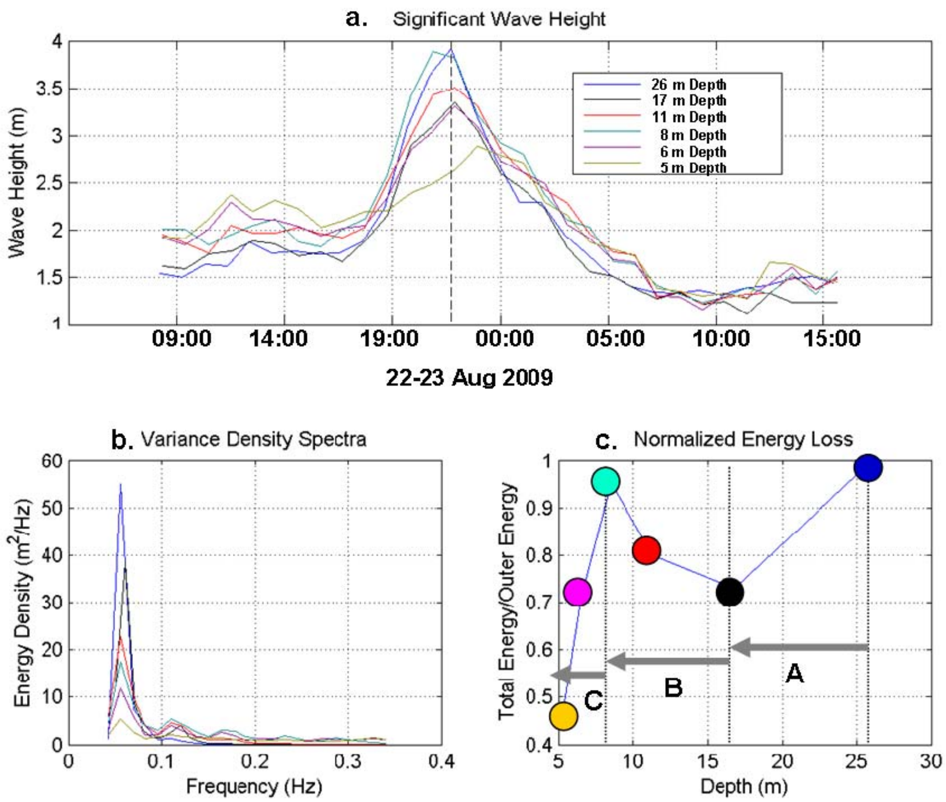

Figure 4. Swell Event 4 (Hurricane Bill) cross-shore array observations: a. Wave height time series at all 6 stations, b. Wave energy-frequency spectra at event peak (denoted by vertical reference line in Figure 4a), c. Attenuation of wave energy across the array at event peak. Dominant processes controlling wave energy across the array are bottom friction and refraction (zone A), shoaling (zone B), and depth breaking (zone C).

4. MODELING

A series of STWAVE-FP modeling runs were conducted to evaluate STWAVE-FP behavior in a swell-dominated sandy coast environment. A key objective was to identify an optimum bottom friction coefficient to use for the Duck wave modeling test bed. This section provides a description of the modeling domains, STWAVE-FP run characteristics, and a summary of results.

Model Set Up

The test bed modeling domain consists of a 50-m horizontal resolution outer grid with a 25-m horizontal resolution nested inner grid. As depicted in Figure 5, the outer grid extends 20.85 km along-shore centered on the measurement array and 16.550 km cross-shore out to the 26-m buoy station. The nested inner grid extends 8.175 km along-shore (also centered on the measurement array) and extends 3.45 km cross-shore out to the 17-m buoy station. The required bathymetry was generated from high-resolution FRF hydrographic surveys and a 10-m Digital Elevation Model (DEM) developed by the Renaissance Computing Institute (RENCI) for the North Carolina Floodplain Mapping Program (NCFMP).

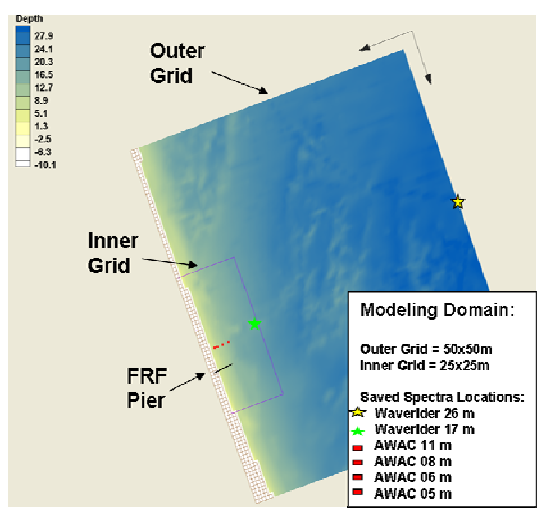

Figure 5. Test bed numerical modeling domain.

STWAVE-FP was set up for the analysis of the bottom friction effects. In order to simulate 'pure' swell events, winds were not provided as an additional forcing across the domain and the STWAVE-FP wind input and whitecapping source terms were deactivated. Furthermore, the STWAVE-FP depth breaking term was turned off to prevent wave energy from being inadvertently lost due to breaking. Argus video records were used to identify the surf zone extent for each event and exclude stations located where depth breaking was occurring. The effects of tide and storm surge on wave evolution were included in the simulations by using FRF water level station observations to uniformly apply water level variations across the entire domain.

Model runs started with an outer grid run forced by directional wave spectra from the 26-m station located along the seaward boundary. Directional wave spectra output along the inner grid oceanic boundaries were then used to force a high-resolution inner-grid run. Model runs were performed on each of our selected events to obtain wave predictions using each of the bottom friction coefficient settings listed in Table 2.

Table 2. STWAVE-FP Bottom Friction Coefficient (*n*) Settings

n	Events
0.02	1,2,3,4
0.07	1,2,3,4
0.10	3,4
0.20	1,2,3

For each run, directional wave spectra were output from both the inner and outer grids at the locations of the cross-shore observation stations (Figure 5). The inner grid output was used in the detailed analysis presented here.

STWAVE Bottom Friction Sensitivity

Evaluation of the STWAVE-FP bottom friction results required a quantification of model run errors at each of the observation station locations. This was accomplished using the USACE Interactive Model Evaluation and Diagnostics System (IMEDS). Using input wave observations, the IMEDS software package performs a robust statistical analysis of model performance at each station (Hanson et al., 2009; Devaliere and Hanson, 2009). As a measure of model run error, we used the wave height bias, computed by IMEDS as

$$b = \frac{1}{n}\sum H_{s\_o} - H_{s\_m},$$

as the difference between the observed significant wave heights H_{s_o} and the modeled significant wave heights H_{s_m} over the entire duration of each event. Comparison of these run errors with associated friction coefficients provides insight into STWAVE-FP behavior in the Duck testbed.

Computed model errors and corresponding roughness coefficients (*n*) at each observation station appear in Figure 6. Event results, shown connected with straight lines, depict a near linear dependence of friction coefficient on wave height bias. Graphically displaying the results in this form allows one to estimate the optimum friction coefficient for each run from the *y*-axis value at 0-m wave height bias value. At each station, most events converge to an optimum friction coefficient between 0.05 and 0.1. However not all events are consistent in this regard. In particular, Event 4 (Hurricane Bill) shows the strongest sensitivity to friction coefficient variations, with rather low optimum friction coefficient values (0.02-0.05) realized at the deeper (8-17 m) stations.

As indicated in Section 1, wave non-linearity can strongly influence wave characteristics in shallow water. The degree of wave non-linearity for a given wave steepness and bottom depth is estimated by the Ursell Number (Holthuijsen, 2007)

$$N_{Ursell} = gHT^2/d^2,$$

with gravitation acceleration g, wave height, H, wave period T and water depth d. As N_{Ursell} increases, the waves become more nonlinear. For waves within the range of $10 < N_{Ursell} < 26$, the weakly nonlinear theory of Stokes is applicable, and for $N_{Ursell} > 26$, the highly nonlinear cnoidal theory is generally applied.

Using the significant wave height (H_s) and peak wave period (T_p) for H and T, respectively, the degree of expected non-linearity of each of our event wave records at the 17-m depth station is shown in Figure 7. Only Event 1 falls below $N_{Ursell} = 10$ and can be expected to behave reasonably within linear theory. Events 2 and 3 are within the Stokes theory domain and Event 4 is within the highly nonlinear cnoidal theory domain. As the waves propagate across the array into shallower water, N_{Ursell} increases further for these events. At the 8-m station, all of the wave events selected are above $N_{Ursell} = 26$ and likely to be nonlinear in nature.

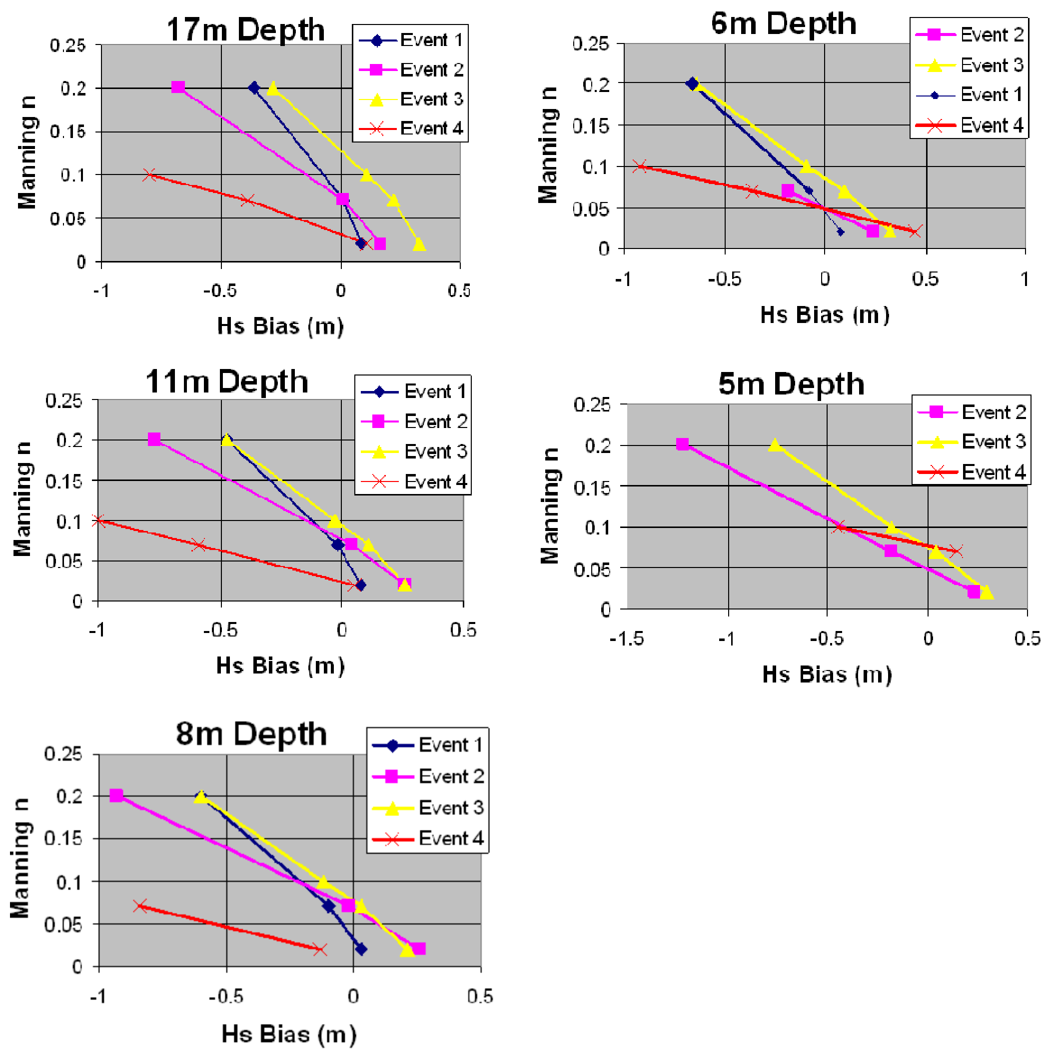

Figure 6. STWAVE-FP event simulation results at each observation station. Significant wave height bias is depicted as a function of selected bottom friction coefficient (n). No observations exist for the 5-m station during Event 1.

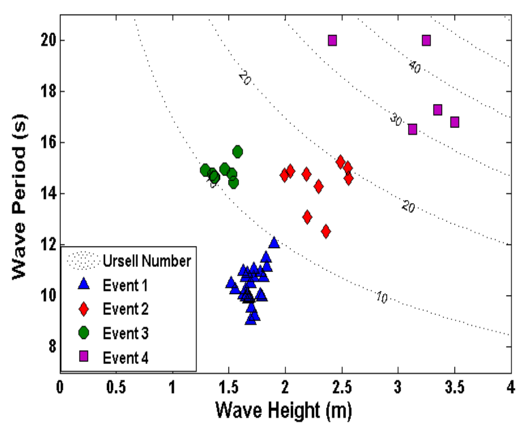

Figure 7. Significant wave height and peak period properties of each swell event at the 17-m station. The degree of wave non-linearity is depicted by the Ursell Number.

Since STWAVE-FP employs linear wave theory to compute wave transformation in shallow water, it can be expected that prediction errors will elevate in increasingly nonlinear wavefield conditions. The anomalous Event 4 results depicted in Figure 6 are a likely result of increased wave non-linearity associated with very long period, high amplitude swells. Accordingly, Event 4 was not used in the friction coefficient analysis.

All the station data from the remaining Events (1-3) are combined to determine an optimal friction coefficient for the Duck test bed. As the results depicted in Figure 8 reveal, we compute a least squares linear regression to describe the variation of n with wave height bias. Selection of a 1st-order fit is reasonable given the high degree of scatter in the data. The y-intercept of this fit yields an optimum friction coefficient of n=0.073. A comparison of observations to STWAVE-FP significant wave heights using n = 0.07 in Events 1-3 appears in Figure 9. The output at the 17-, 11-, 8-, 6-, and 5-m stations are included. A reasonably acceptable fit is obtained with both a low bias (b = -0.018 m) and a low root-mean-square error (E_{RMS} = 0.147 m).

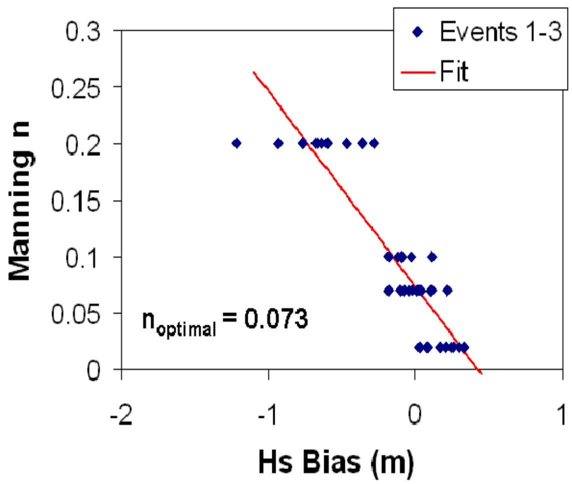

Figure 8. Selection of optimal friction coefficient using STWAVE results from Events 1-3 at all 5 output stations. The y-intercept of a linear fit through the data is at n=0.073.

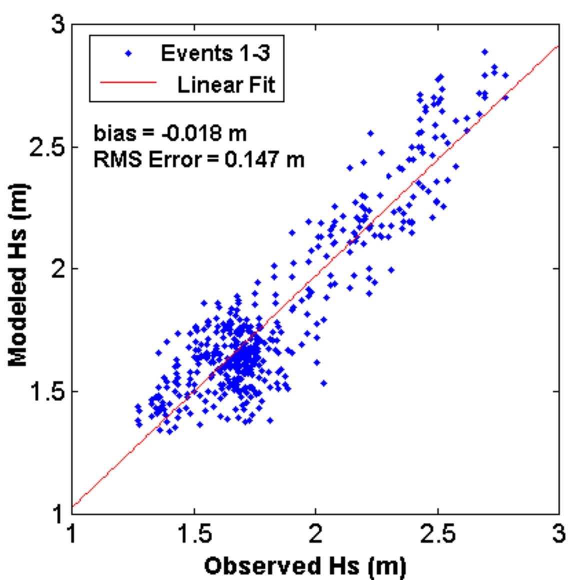

Figure 9. STWAVE-FP significant wave height simulation results for Events 1-3 using a bottom friction coefficient of n = 0.07. Data are combined from all 5 observation stations.

5. SUMMARY

The objectives of this investigation were to evaluate STWAVE-FP behavior in a swell-dominated, sandy coast environment and to determine an optimum bottom friction coefficient to use with the manning's n formulation. The FRF coastal wave modeling test bed at Duck, North Carolina proved to be an ideal location to conduct this study. Swell event data from the FRF cross-shore wave and current array provided the necessary ground truth on which to evaluate STWAVE-FP sensitivity to the friction coefficient n.

Nonlinearity in the wavefield becomes a critical factor as waves evolve into shallow water. One must exercise caution when interpreting shallow-water results from numerical wave models based on linear wave theory. For this analysis, the swell produced from Hurricane Bill (H_s>3m; $T_p \geq$ 18s) was shown to be highly nonlinear (N_{Ursell}>30) and hence excluded from the analysis.

The mean wave height bias was used as an overall indicator of model skill in replicating the remaining 3 wave events. STWAVE-FP manning's n friction factor was varied in repeated event runs to identify an optimum value n for the Duck test bed. The dependence of the friction factor n on wave height bias can be approximated by a linear relationship. This allows calculation of an optimum n from the entire set of runs (excluding the Hurricane Bill data). Based on these preliminary results, the optimum friction coefficient for the Duck test bed is n = 0.073. Use of n = 0.07 for simulating the events investigated here results in low prediction errors at all stations.

Additional research will focus on applying this friction coefficient to a wider range of windsea and swell events to further document STWAVE-FP model performance in this dynamic environment.

ACKNOWLEDGEMENTS

The authors are grateful for many helpful STWAVE discussions with Jane Smith and wave physics discussions with Chuck Long and Don Resio. We would like to thank Eve Devaliere for her contributions to the IMEDS and XSHORE data analysis packages, and Philip Balitsky for developing an early version of XSHORE. Kate Brodie and Heidi Wadman provided valuable technical and editorial comments. This project was made possible thanks to funding from the U.S. Army Corps of Engineers MORPHOS program.

REFERENCES

Cavaleri, L. et al., 2007. Wave modeling – The state of the art, Progress in Oceanography, 75, pp. 603-674.

Devaliere, E-M., and J.L. Hanson, 2009. IMEDS Interactive Model Evaluation and Diagnostics System V2.6 Users Guide, US Army Corps of Engineers, Field Research Facility, http://www.frf.usace.army.mil/morphos/imeds/ref.shtml.

Hanson, J.L., B. Tracy, H. Tolman and R. Scott, 2009. Pacific hindcast performance of three numerical wave models, *J. Atmos. Oceanic Technol*., 26, 1614-1633.

Hanson, J.L. and O.M. Phillips, 2001. Automated analysis of ocean surface directional wave spectra, *J. Atmos. Oceanic Technol*., 18, 277-293.

Holthuijsen, L.H., 2007. Waves in Oceanic and Coastal Waters, Cambridge University Press, 387 pp.

Longuet-Higgins, M.S., Cartwright, D.E., Smith, N.D., 1963. Observations of the directional spectrum of sea waves using the motions of a floating buoy. In: Ocean Wave Spectra. Prentice-Hall, Englewood Cliffs, NJ, pp. 111–136

Smith, J.A., 2007. Full-Plane STWAVE with Bottom Friction: II. Model Overview, US Army Corps of Engineers, Engineer Research and Development Center Technical Report ERDC/CHL CHETN-1-75, 15p.