WAVE TRANSFORMATION MODELING WITH BOTTOM FRICTION APPLIED TO SOUTHEAST OAHU REEFS

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1. INTRODUCTION

A hydrodynamic modeling study was performed for the Southeast Oahu Regional Sediment Management demonstration project by the Engineer Research and Development Center, Coastal and Hydraulics Laboratory to provide the Corps of Engineers Honolulu District with a tool for understanding wave transformation and nearshore circulation in Southeast Oahu from Mokapu Point to Makapuu Point. The significant reef system in the region was a particular challenge for modeling wave transformation, therefore the Corps' widely-used wave model, STWAVE (Smith 2001, Smith et al. 2001), was enhanced to include the effect of bottom friction (Smith 2007). Development of a bottom friction capability in STWAVE was completed and first applied to represent dissipation over the extensive reefs in the Southeast Oahu study area and wetlands in southern Louisiana.

2. BOTTOM FRICTION FORMULATION

STWAVE includes two formulations for bottom friction. The first is the JONSWAP formulation (Hasselmann et al. 1973, Padilla-Hernandez and Monbaliu 2001), where the spectral energy loss from bottom friction is formulated as a sink term, S_{bf}, in the energy balance equation,

$$S_{bf} = \frac{-1}{g} c_f \frac{\sigma^2}{\sinh^2 kd} E(f,\alpha) \tag{1}$$

where g is the acceleration of gravity, c_f is the friction coefficient, σ is the angular frequency, k is wave number, d is water depth, E is wave energy density divided by $(\rho_w g)$, where ρ_w is density of water, f is wave frequency, and α is wave direction.

A single friction coefficient c_f can be applied to the entire STWAVE domain or a range of friction values can be applied on a cell-by-cell basis. For the JONSWAP bottom friction formulation, c_f is specified as Γ/g, where the recommended values of Γ are in the range 0.038 to 0.067 m^2/s^3 (or model input values of c_f = 0.004 to 0.007) for sand beds based on experiments in the North Sea. Equation 1 has a weak inverse dependence on water depth (related to the increase in bottom wave orbital velocity as the relative depth, kd, decreases).

A Manning formulation is also available in STWAVE, based on Holthuijsen (2007),

$$S_{bf} = \frac{-1}{g}\left(\frac{gn^2}{d^{1/3}}\right)\frac{\sigma^2}{\sinh^2 kd} E(f,\alpha) u_{rms} \tag{2}$$

where the value of n is specified as input to STWAVE (either spatially constant or variable) and u_{rms} is the root-mean-square bottom velocity. With the Manning formulation, bottom friction dissipation has an additional inverse dependence on water depth. Estimates of Manning coefficients are available in most fluid mechanics reference books (e.g., 0.01 to 0.05 for smooth to rocky/weedy channels), however it is recommended that the specification of c_f or n be validated with field measurements.

3. FIELD DATA AND VALIDATION

As noted, application of this model capability to a specific site requires validation to field data. Field (wave) data were collected in 2005 both seaward and landward of the Southeast Oahu reef for comparison to model results (Figure 1). However, in the initial application, an examination of the 2000-2004 wave record at Coastal Data Information Program (CDIP) Station 098 (Mokapu Point) provided a discrete set of 134 wave conditions that are representative of long-term offshore wave conditions in this area. These conditions first simulated without bottom friction were repeated with the revised STWAVE, applying a JONSWAP bottom friction coefficient typical for reefs of c_f =0.05 (approximately one order of magnitude greater than the JONSWAP value for a sandy bottom) over the entire model domain. The offshore wave height range was defined at 0.5-m intervals from 0.75 m to 2.75 m and at a 0.75-m interval to 3.5 m. The wave period range was 6 to 16 sec at a 2-sec interval. The wave directions were incremented by 22.5 deg from -22.5 deg to 90 deg, relative to True North. This application provided a sense of the magnitude of the dissipation provided by the inclusion of bottom friction in the model formulation. A comparison of wave heights at one nearshore location in Waimanalo Bay slightly north of ADV3 (Cell (229,506) in Figure 1) was made. The offshore to nearshore comparison without bottom friction shows a reduction in wave height of 38% (Figure 2). With bottom friction, the reduction in wave height is 84%. A comparison of the nearshore wave heights with and without bottom friction shows that with the inclusion of bottom friction, wave heights range from 18% to 38% of the previous results that did not include bottom friction. On average, the wave height was 26% of the without bottom friction value at the selected location. Waves from the northeast refract slightly (1 deg) less with the inclusion of bottom friction. Waves from the east-southeast refract slightly (1 deg) more with the inclusion of bottom friction.

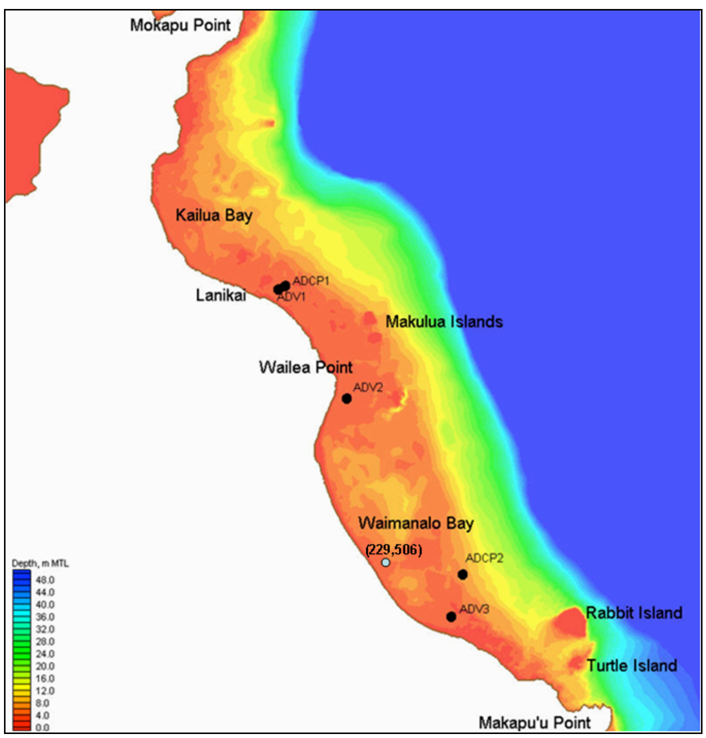

Figure 1. Gauge locations and reef bathymetry

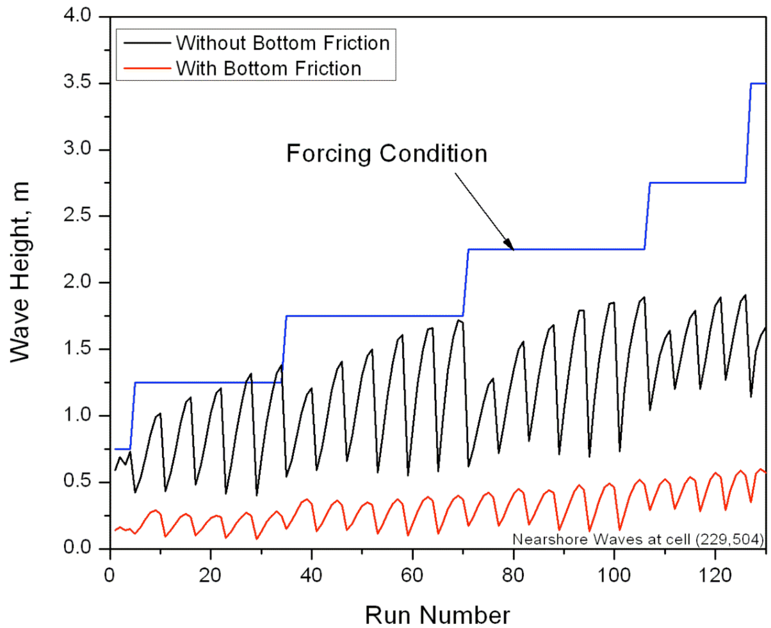

Figure 2. Comparion of predicted wave heights at cell (229, 506) with and without bottom friction in STWAVE

STWAVE was next applied in the model validation process. The August 2005 model validation time period corresponded to a portion of the field data collection time period (9 August through 14 September 2005). CDIP Buoy data for August 2005 were extracted from the CDIP website for every 3-hr interval of August 2005. For each of these measured wave conditions, TMA (shallow-water) spectra were generated by applying the Surface-water Modeling System (SMS) spectral wave generation software (Zundel 2005). These spectra were then applied to the offshore boundary of the model domain. Note that analysis was done to compare the waves at the 300-m depth STWAVE boundary and the 100-m depth gauge location by applying the University of Delaware Hydrodynamic Wave Calculator applet application (http://www.coastal.udel.edu/faculty/rad/wavetheory.html). It was found that the difference in wave height from the 300 m to 100 m depth is small (approximately 4% for periods <15 sec, which accounts for 98% of the waves) and the offshore gauge data were applied at the STWAVE boundary without back refracting to the 300 m water depth.

Initially, a constant bottom friction coefficient was applied to each cell of the STWAVE domain that represented the reef. Several simulations with different spatially constant Manning and JONSWAP bottom friction coefficients ranging from 0.15 to 0.25 (Manning) and 0.04 to 0.12 (JONSWAP) were made to examine the range of response (wave height) at the gauge locations. These initial simulations indicated that without bottom friction, wave heights at ADV1 are reduced on average by 21% relative to the offshore wave height. Bottom friction reduces wave height at ADV1's location by 64% for a JONSWAP bottom friction coefficient of 0.04 (wave height is 36% of the offshore wave height), by 71-76% for a bottom friction value of 0.05 (wave height is 24-29% of the offshore wave height), and by 93% for a bottom friction value of 0.12 (wave height is 7% of the offshore wave height). Applying a Manning friction coefficient to the reef resulted in average wave height reductions of 62-80%. The range of response indicates the importance of selecting the appropriate bottom friction value to represent the reefs in the study area. Measurements at ADV1 indicate a reduction in average wave height relative to the average offshore wave height of 72-74%, therefore a JONSWAP value of 0.05 and a Manning coefficient of 0.20 were selected for further validation.

In the validation simulation, a variable bottom friction field with a Manning coefficient of 0.20 applied to the reef region, 0.19 around the offshore islands, and 0.02 in the offshore regions was utilized. JONSWAP coefficients were 0.05 applied to the reef region, 0.09 around the offshore islands, and 0.006 in the offshore regions. In addition, water levels were adjusted to account for the measured tidal variation during this time period. Figures 3-8 show the wave height time series generated by STWAVE at the gauge locations without bottom friction and for two simulations with bottom friction (with and without tide), along with the field measurements at these locations. The model results for the ADV1 location follow the magnitude and trend of the data well, particularly with the JONSWAP friction formulation. Note that the inclusion of tidal fluctuation in the model improves the response/comparison to gauge data, particularly with the Manning friction formulation. Model results at the ADV2 location tend to under-predict the measured wave height with the selected validation friction coefficient. Model results at the ADV2 location show more of a signal (change in wave height with time similar in pattern to the offshore forcing), whereas the measurements show much less variability (nearly constant wave height due to the depth limitation of the reef). Model results at ADV3 tend to over-predict the measured wave height when the offshore waves are greater than 1.3 m.

Another indicator of the model ability to estimate wave transformation over a reef is the Model Performance Index (MPI) (Smith 2000). The MPI is a measure of the models ability to capture the transformation from offshore to nearshore that is observed in the field data.

$$MPI = 1 - Error_{rms} / Changes_{rms} \tag{3}$$

where $Error_{rms}$ is the root-mean-square error of the model compared to the ADV gauge data and $Changes_{rms}$ is the root-mean-square change from the offshore data to the nearshore data. Values of the MPI near unity indicate good agreement. For the initial simulations with constant bottom friction applied to the reef, the MPI values are 0.92 to 0.96 for the Manning representation of bottom friction and 0.89 to 0.94 for the JONSWAP representation of bottom friction.

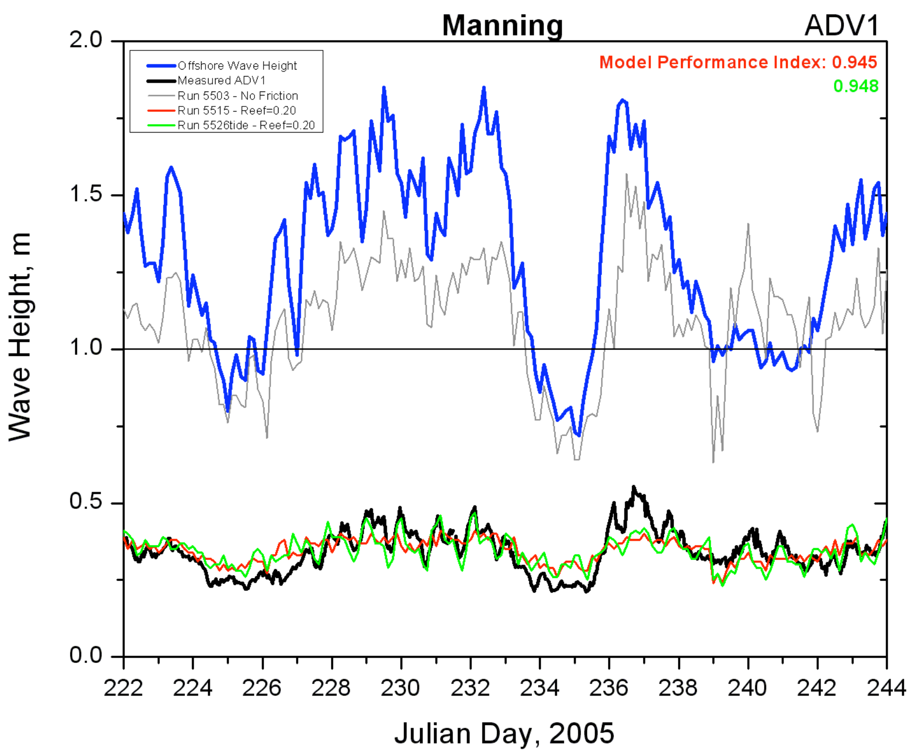

Figure 3. ADV1: Measured and modeled wave heights with Manning friction formulation

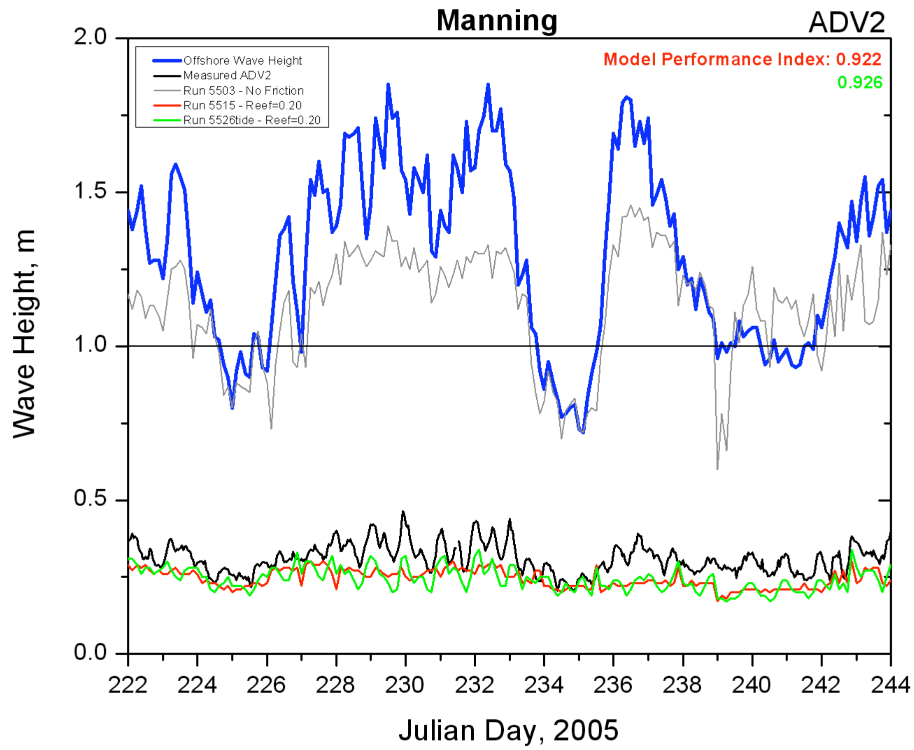

Figure 4. ADV2: Measured and modeled wave heights with Manning friction formulation

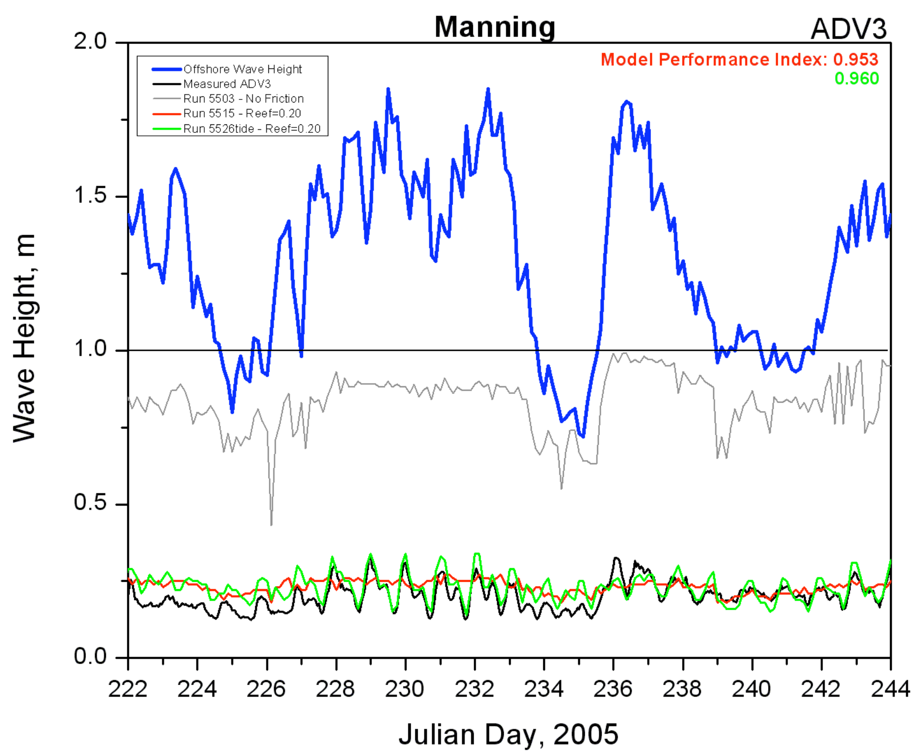

Figure 5. ADV3: Measured and modeled wave heights with Manning friction formulation

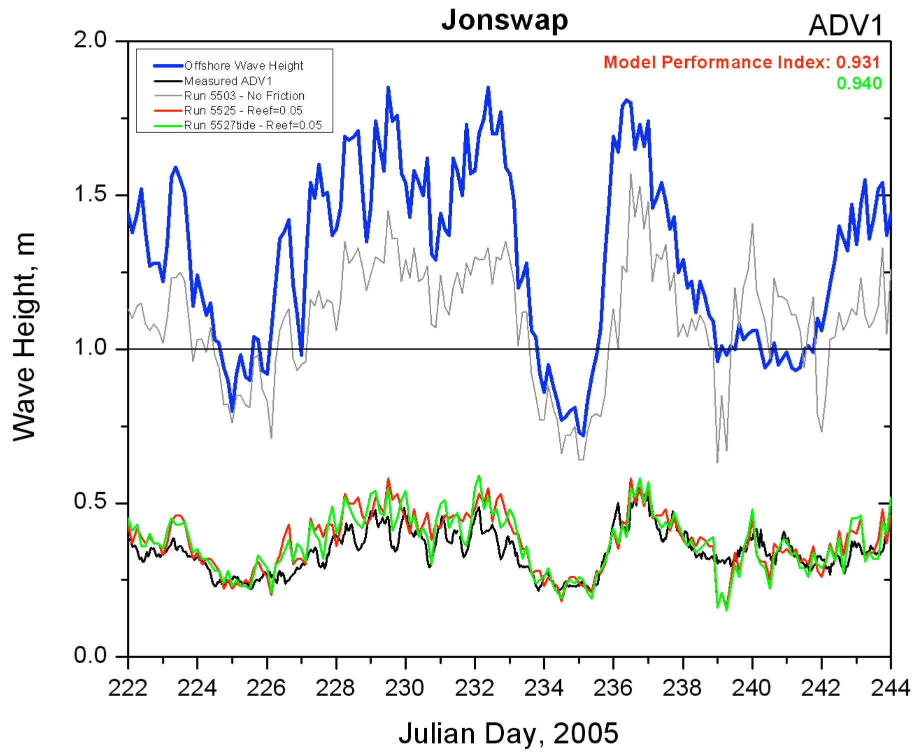

Figure 6. ADV1: Measured and modeled wave heights with JONSWAP friction formulation

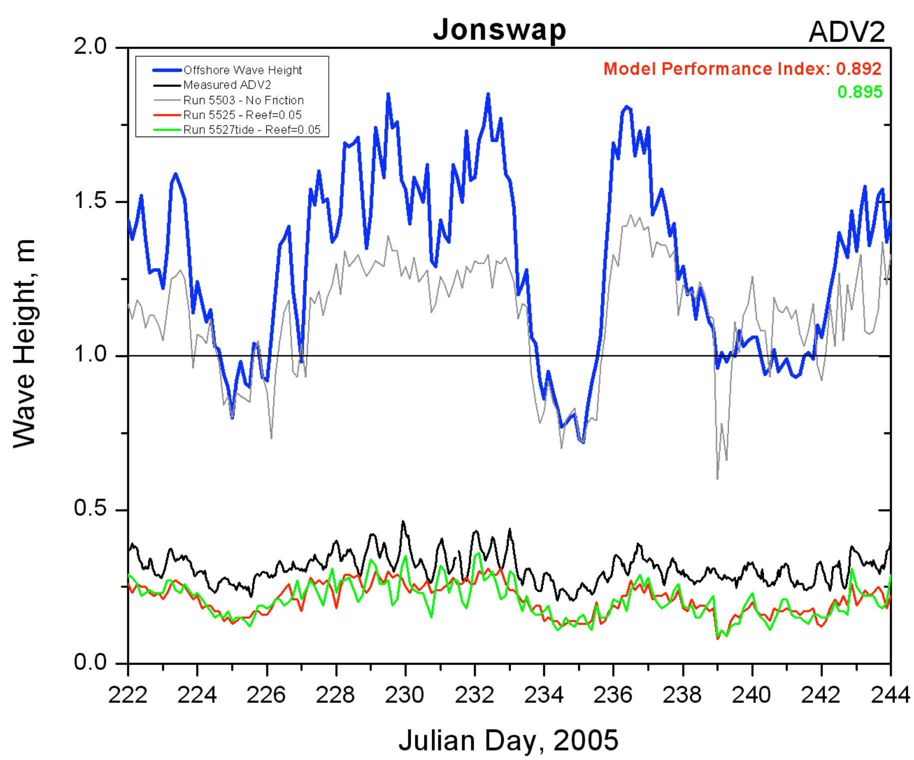

Figure 7. ADV2: Measured and modeled wave heights with JONSWAP friction formulation

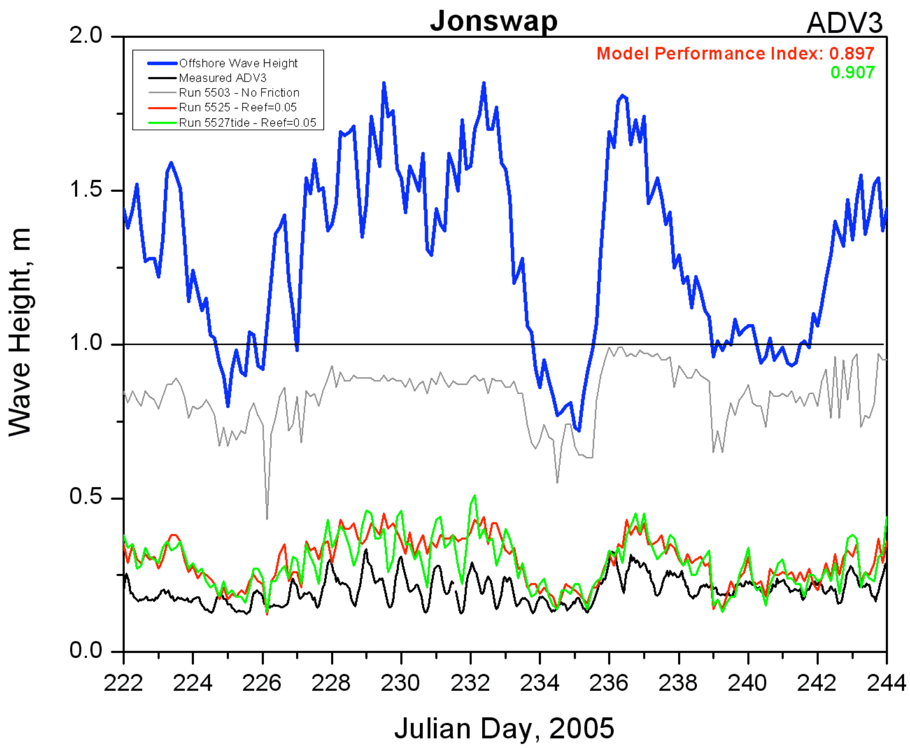

Figure 8. ADV3: Measured and modeled wave heights with JONSWAP friction formulation

Overall, all three measurement locations experience low wave energy relative to the offshore waves, due to the relatively mild tradewind conditions and wave dissipation over the reef. The field measurements range in wave height from 0.12 to 0.69 m for the data collection time period and the model results range from 0.08 to 0.59 m. The STWAVE model captures the large reduction in wave height from the offshore location to the three nearshore locations. It is noted that the coral reefs in this region are described as "mushroom fields". Some areas of the reef are more solid and some areas have gaps and holes in the reef. This level of detail was not applied to the friction representation of the reef. A possible improvement to the results, particularly at ADV3, could be made by revising the friction coefficients to represent the spatial variability of the reef roughness.

For the reasons outlined above, additional model simulations with variable bottom friction were made for the field data collection time period and model results were compared to field data. Without detailed knowledge of the contiguous/non-contiguous areas of the reef, an educated attempt was made to represent the variations in the reef. The center section of the reef was given a smaller friction coefficient and the southern portion of the reef was given a larger coefficient (Figure 9). These adjusted values were selected based upon the under/over prediction of wave height at ADV2 and ADV3, respectively, in the previous simulation. Tidal fluctuation was also included in these simulations. As shown in Figures 10-15, with a variable bottom friction coefficient to represent variability in the reef structure, model results compare extremely well with the data at all three gauge locations with both the Manning and the JONSWAP friction formulations. The MPI values are 0.948 to 0.970 for the Manning simulations and 0.951 to 0.953 for the JONSWAP simulations. The magnitude and trend as well as the tidal fluctuation exhibited by the data are all captured by the model.

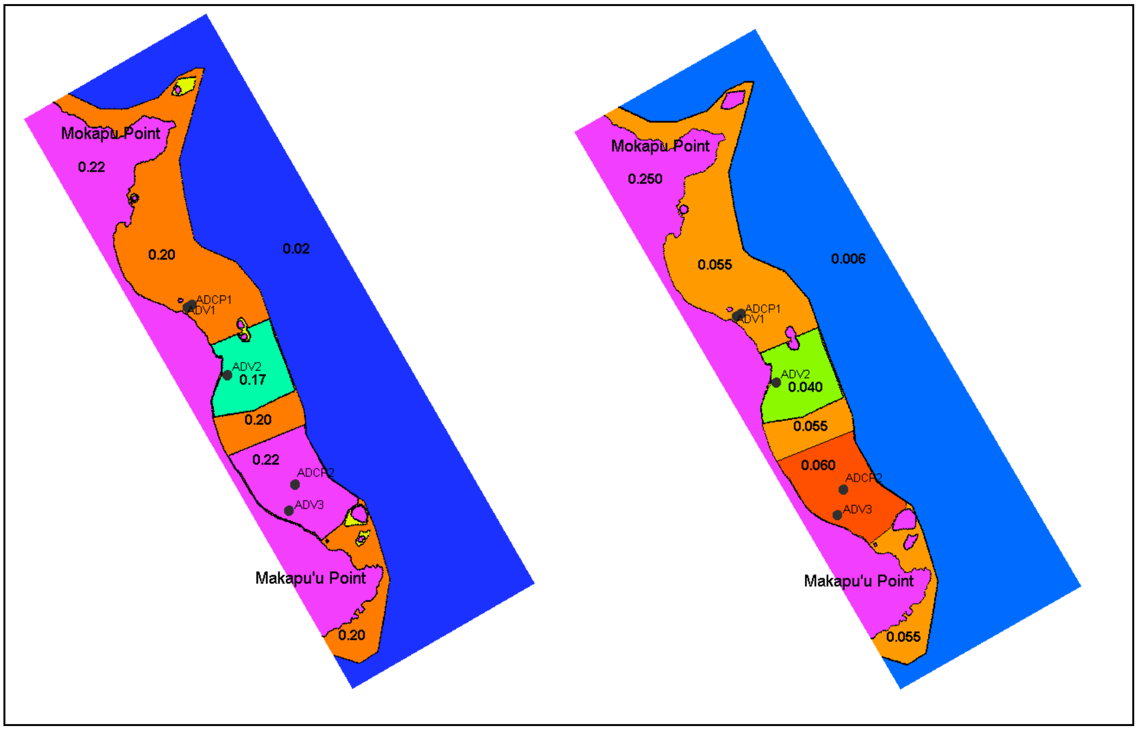

Figure 9. Manning and JONSWAP friction coefficients applied to STWAVE domain

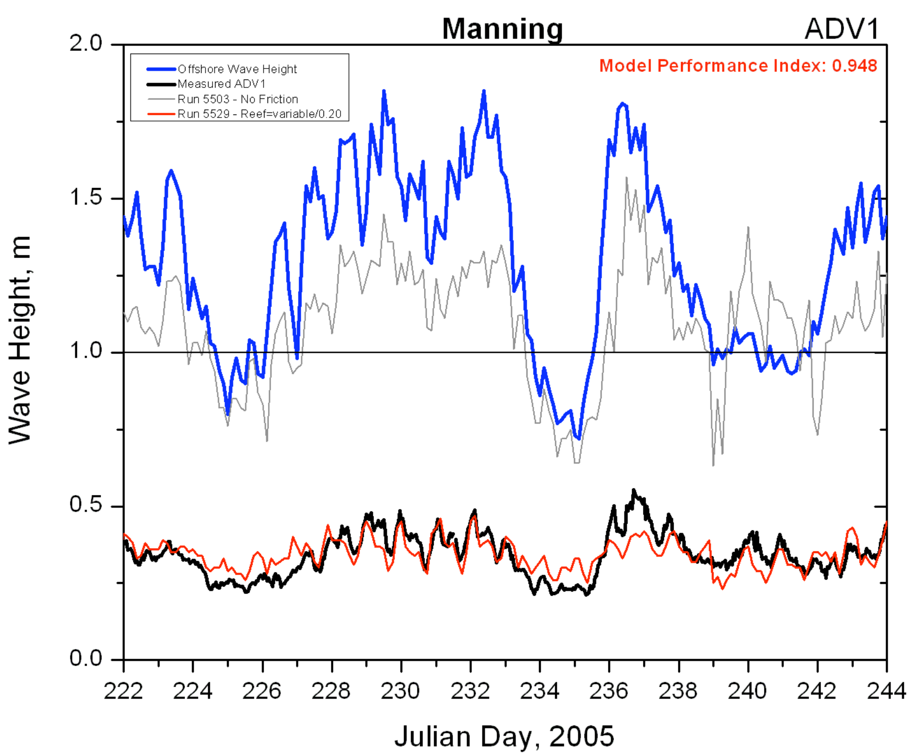

Figure 10. ADV1: Measured and modeled wave heights with variable Manning friction formulation

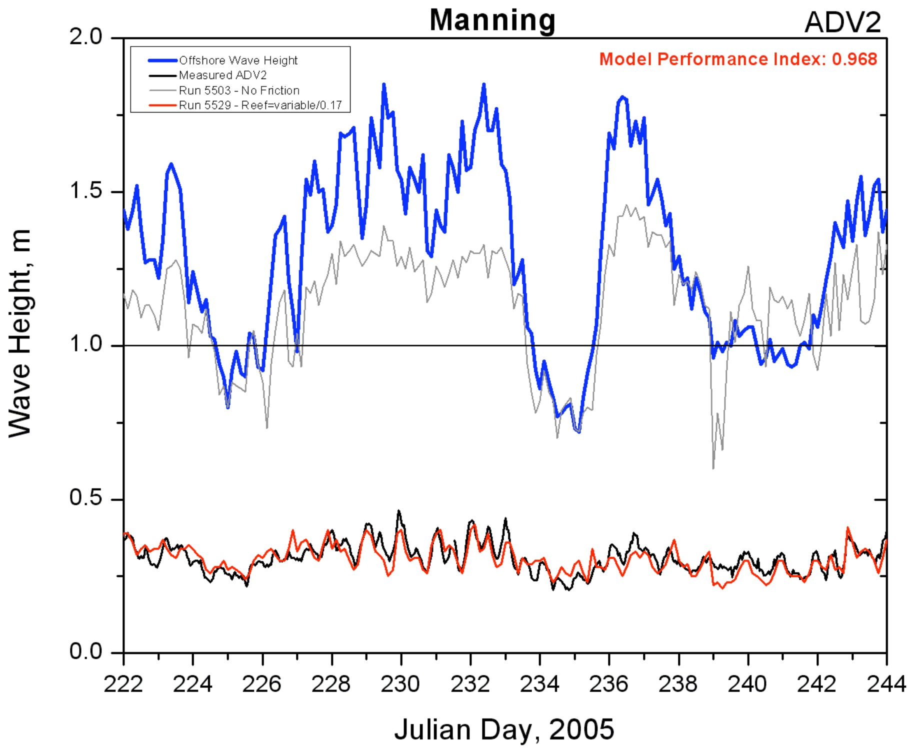

Figure 11. ADV2: Measured and modeled wave heights with variable Manning friction formulation

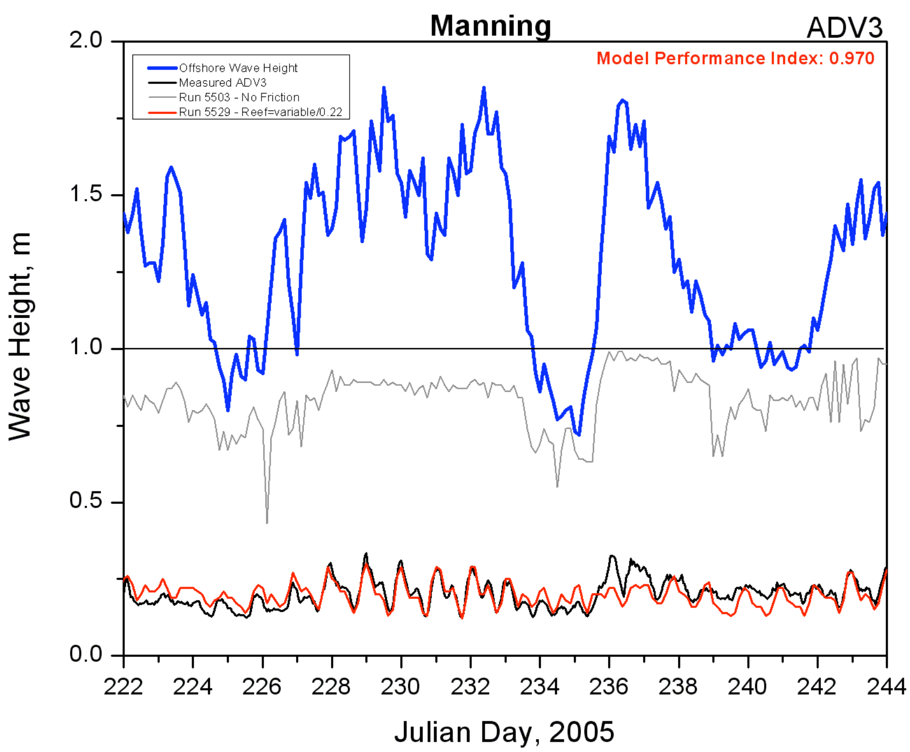

Figure 12. ADV3: Measured and modeled wave heights with variable Manning friction formulation

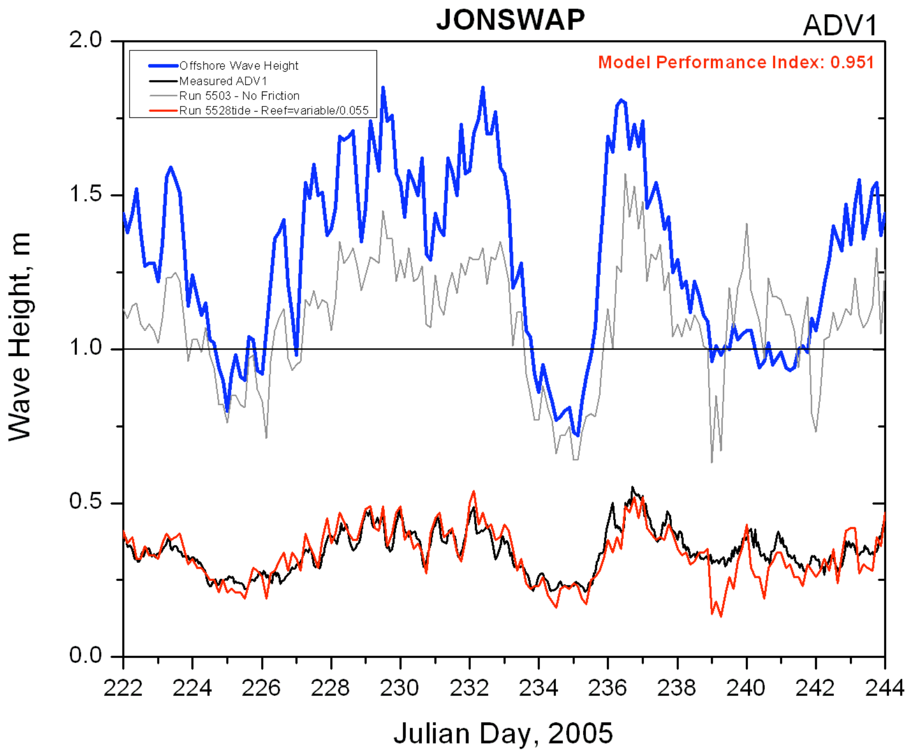

Figure 13. ADV1: Measured and modeled wave heights with variable JONSWAP friction formulation

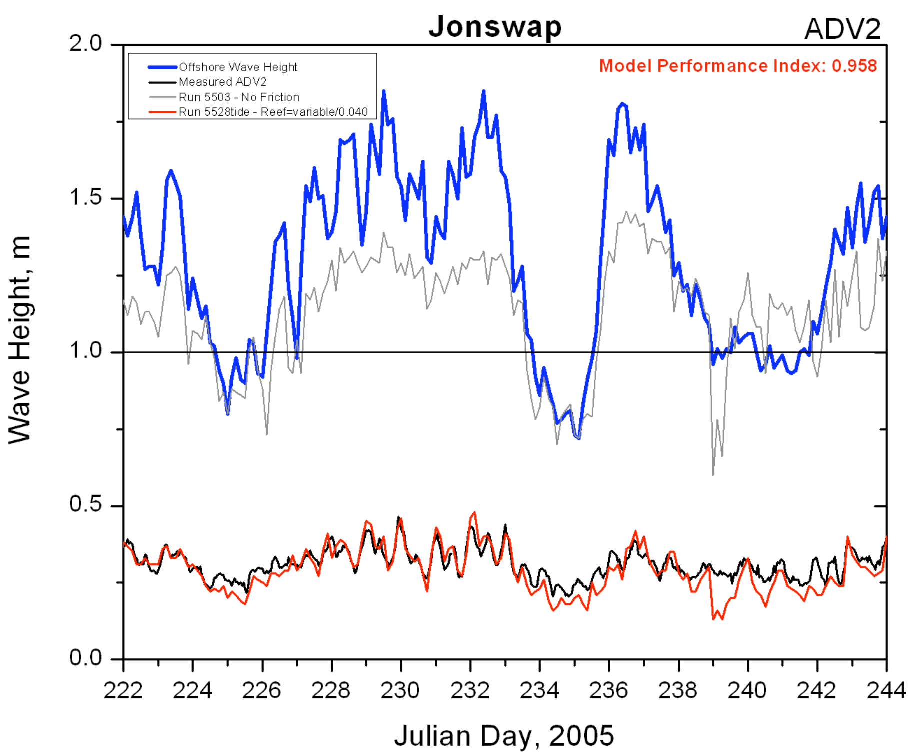

Figure 14. ADV2: Measured and modeled wave heights with variable JONSWAP friction formulation

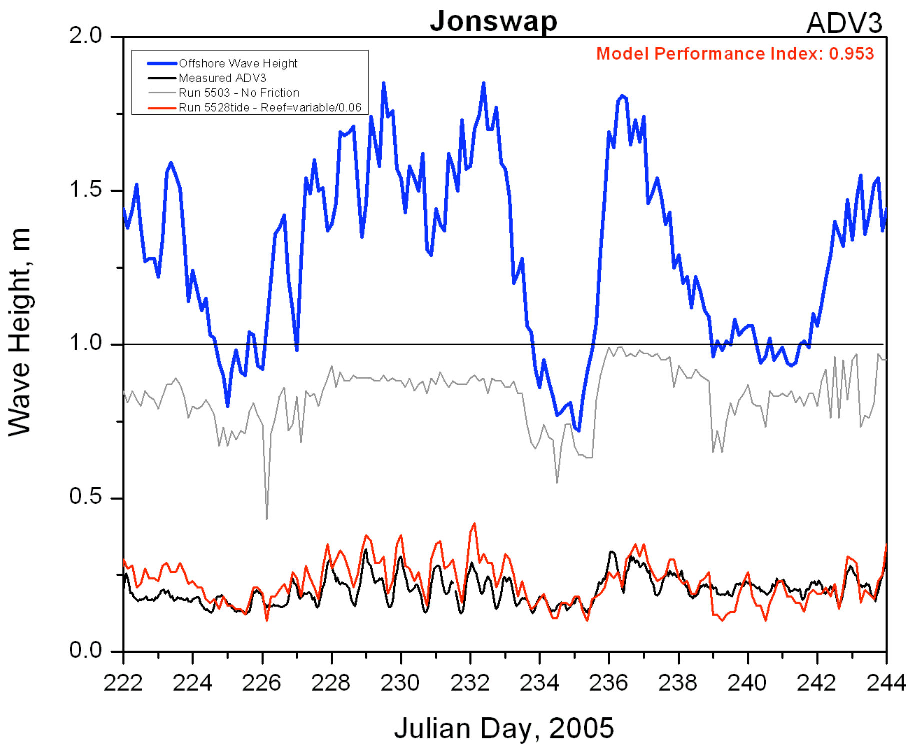

Figure 15. ADV3: Measured and modeled wave heights with variable JONSWAP friction formulation

4. SUMMARY

Development of a bottom friction capability in STWAVE was implemented and applied to the extensive reefs in the Southeast Oahu study area. Values of the bottom friction coefficient applied for coral reefs ranged from Manning *n* of 0.15 to 0.25 and JONSWAP coefficient of 0.04 to 0.12. The range of response from these applications indicates the importance of selecting the appropriate bottom friction value to represent the reefs in a given study area. Wave height measurements landward of the Oahu reef indicate a reduction in average wave height relative to the average offshore wave height of 72-74%, therefore a JONSWAP value of 0.05 and a Manning coefficient of 0.20 were selected for further validation.

In the validation simulation, a variable bottom friction field with a Manning coefficient of 0.20 and a JONSWAP coefficient of 0.05 were applied to the reef. In addition, water levels were adjusted to account for the measured tidal variation during this time period. The model results for the ADV1 location follow the magnitude and trend of the data well, particularly with the JONSWAP friction formulation and the inclusion of tidal fluctuation in the model. The tidal fluctuation improves the response/comparison to gauge data, particularly with the Manning friction formulation. Model results at the ADV2 location tend to under-predict the measured wave height with the selected validation friction coefficient and over-predict the measured wave height at ADV3. For these initial simulations, with constant bottom friction applied to the reef, the MPI values indicate that the model is capturing wave transformation and dissipation over the reef. MPI values for these simulations are 0.92 to 0.96 for the Manning representation of bottom friction and 0.89 to 0.94 for the JONSWAP representation of bottom friction.

The STWAVE model captures the large reduction in wave height from the offshore location to the three nearshore locations; however, the coral reefs in this region are described as “mushroom fields” with some areas of the reef being more solid and some areas having gaps and holes in the reef. Additional model simulations with variable bottom friction were made for the field data collection time period and model results were compared to field data. Without detailed knowledge of the contiguous/non-contiguous areas of the reef, an educated attempt was made to represent the variations in the reef. The center section of the reef was given a smaller friction coefficient and the southern portion of the reef was given a larger coefficient.

These adjusted values were selected based upon the under/over prediction of wave height at ADV2 and ADV3, respectively, in the previous simulation. Tidal fluctuations were also included in these simulations. With a variable bottom friction coefficient to represent variability in the reef structure, model results compare extremely well with the data at all three gauge locations with both the Manning and the JONSWAP friction formulations. The MPI values are 0.95 to 0.97 for the Manning simulations and 0.95 to 0.95 for the JONSWAP simulations. The magnitude and trend as well as the tidal fluctuation exhibited by the data are all captured by the model.

5. ACKNOWLEDGEMENTS

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