# INCIDENT BOUNDARY CONDITIONS FOR WAVE TRANSFORMATION

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## 1. INTRODUCTION

The nearshore wave transformation model STWAVE is used to transform hindcast wave time histories to the shore to estimate longshore sediment transport rates. These transport rates are used to evaluate engineering design of beach fills and coastal shore protection structures. The boundary conditions used to force STWAVE are typically derived from the Wave Information Studies (WIS) wind-wave hindcast database. In the past, only bulk wave parameters (height, period, and direction) were available from the database, and these parameters were used to generate parametric spectra to drive the transformation model. Thus, the detailed spectral information from the hindcast was lost in the transition to the nearshore. The updated WIS hindcast is archiving wave spectra, as well as parameters, for intermediate-depth sites along the coast. The purpose of this paper is to evaluate the feasibility of driving a nearshore model with hindcast spectra versus parameters for a two-year period at Duck, North Carolina. Comparisons are made with nearshore gauge measurements. The relative impacts of the incident boundary input on sediment transport estimates for the two-year period are evaluated.

## 2. WAVE MODELING

The spectral wave model STWAVE is used to transformation hindcast waves from a depth of 25 m to 8 m. The input hindcast information from WIS and the STWAVE model are discussed in the following sections.

### 2.1 Wave Information Studies

The role of WIS is to generate wave climatologies for U.S. coastlines to provide wave information for coastal engineering studies. For many project sites, WIS hindcasts provide the only wave information available for design. Even when field measurements are available, they typically lack the temporal coverage necessary to represent the local wave climate. WIS hindcasts have covered the period 1956-1995. WIS uses the numerical wave generation model WISWAVE (Resio 1981, Hubertz 1992) together with input wind fields and bathymetry to simulate wave generation and propagation. WISWAVE is a second-generation discrete directional spectral wave model. The model includes source and sink terms of atmospheric input, parameterized nonlinear interactions, and dissipation. WIS recently completed an updated hindcast of the U.S. Atlantic and Gulf of Mexico coastal wave climate (Tracy 2002) for 1990-1999. The updated hindcast employs improved wind fields, higher spatial resolution (nested from 1 deg to 1/4 deg to 1/12 deg), and upgrades to WISWAVE wind input and nonlinear source terms. The update also included a comprehensive verification effort. Nearshore wave information is also being saved at higher resolution ($1/12^{th}$ deg along the coast in depths of 15-30 m for the Atlantic). In addition to the wave parameters (height, period, and direction) saved in previous hindcasts, the full spectra are being archived at the nearshore save locations as well. Wave spectra are available every 3 hrs and parameters are available every 1 hr, starting at 0 hr Greenwich Mean Time (GMT) each day.

The Atlantic WIS station closest to the Field Research Facility (FRF) at Duck, North Carolina, is Station 218 located at 36.25 deg N and 75.58 deg W in a depth of 25 m. The years 1997 and 1998 was chosen for analysis because the hindcast for these years was complete at the time of this study and a nearly complete nearshore wave measurement record at the FRF was available. WIS data extracted from the archive for Station 218 includes the wave parameters zero-moment wave height ($H_{mo}$), peak spectral period ($T_p$), and mean wave direction ($\theta_m$) and the wave spectra. The spectra include 20 frequency bins (ranging from 0.03 to 0.30 Hz) and 16 direction bins (22.5 deg resolution). Parametric wave energy in frequencies higher than 0.30 Hz are included in the wave heights, but not in the spectra.

The closest wave buoy to WIS Station 218 is the National Data Buoy Center Buoy 44014 located at 36.58 deg N and 74.83 deg W in depth of 48 m. In addition to the nearshore save locations, WIS saves wave model results for all active buoy locations for verification. For 1998, data from Buoy 44014 were available for the months of June through December. Estimates of WIS errors, based on Buoy 44014, are given in Table 1. The bias and root-mean-square (RMS) error are defined as:

$$Bias = \frac{\sum (P_{measured} - P_{simulated})}{n} \tag{1}$$

$$RMS\ Error = \sqrt{\frac{\sum (P_{measured} - P_{simulated})^2}{n}} \tag{2}$$

where $P_{measured}$ is the measured wave parameter (buoy), $P_{simulated}$ is the modeled wave parameter (WIS), and *n* is the number of values.

**Table 1. WIS Errors based on Buoy 44014**

| Wave Height | | Peak Wave Period | | Directional Bias (deg) |
|---|---|---|---|---|
| Bias (m) | RMS Error (m) | Bias (sec) | RMS Error (sec) | |
| -0.04 | 0.33 | -0.87 | 2.5 | -7.9 |

2.2 STWAVE

The numerical model STWAVE (Resio 1987, 1988; Smith et al. 2001) was used to transformation the WIS hindcast from the 25-m depth at Station 218 to 8-m depth for comparison to the FRF 8-m directional array. STWAVE numerically solves the steady-state conservation of spectral wave action balance along backward-traced wave rays:

$$(C_{ga})_x \frac{\partial}{\partial x} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} + (C_{ga})_y \frac{\partial}{\partial y} \frac{C_a C_{ga} \cos(\mu - \alpha) E(f,\alpha)}{\omega_r} = \sum \frac{S}{\omega_r} \tag{3}$$

where

$C_{ga}$ = absolute wave group celerity
*x,y* = spatial coordinates, subscripts indicate *x* and *y* components
$C_a$ = absolute wave celerity
$\mu$ = current direction
$\alpha$ = propagation direction of spectral component
*E* = spectral energy density
*f* = frequency of spectral component
$\omega_r$ = relative angular frequency (frequency relative to the current)
*S* = energy source/sink terms

The source and sink terms include wind input, nonlinear wave-wave interactions, dissipation within the wave field, and surf-zone breaking. The terms on the left-hand side of Equation 3 represent wave propagation (refraction and shoaling), and the source/sink terms on the right-hand side of the equation represent energy growth or decay in the spectrum.

The assumptions made in STWAVE are as follows:

- Mild bottom slope and negligible wave reflection.

- Spatially homogeneous offshore wave conditions.
- Steady waves, currents, and winds.
- Linear refraction and shoaling.
- Depth-uniform current.
- Negligible bottom friction.

STWAVE is a half-plane model, meaning that only waves propagating toward the coast are represented. Waves reflected from the coast or waves generated by winds blowing offshore are neglected. Wave breaking in the surf zone limits the maximum wave height based on the local water depth and wave steepness. STWAVE is a finite-difference model and calculates wave spectra on a rectangular grid with square grid cells. The model outputs include zero-moment wave height, peak wave period ($T_p$), and mean wave direction ($\alpha_m$) at all grid points and two-dimensional spectra at selected grid points.

The STWAVE bathymetry grid was developed using high-resolution data available from the FRF. The grid extends from the shoreline to WIS Station 218 in 25-m water depth. The grid is 163 cells across the shore and 260 cells along the shore with a resolution of 100 m. The grid is orientated with *x*-axis perpendicular to the shoreline (waves from 70 deg are parallel to the grid *x*-axis). Input wave spectra were generated using two methods: 1) WIS spectra were truncated to align with the STWAVE half-plane grid. Model runs using the WIS spectra as input will be referred to as the 'spectral results'. 2) WIS-generated bulk wave parameters were used to generate spectra of the TMA shape (Bouws et al. 1985) in frequency and a $\cos^n$ directional distribution, with wave height, peak period, and mean direction defined by WIS. The values of the spectral peakedness parameters and spreading exponent used varied with peak period as estimated by Thompson et al. (1996). Model runs using the WIS parameters as input will be referred to as the 'parametric results'. Local wind speed and direction used in the simulations were taken from WIS Station 218. Tide elevation measured at the 8-m depth at the FRF was input as a tidal adjustment. When measured tide was not available, the predicted tide was substituted. Currents were neglected in the simulations.

## 3. COMPARISONS TO FIELD MEASUREMENTS

Wave measurements from the nearshore 15-element array of bottom-mounted pressure gauges (Gauge 111), located north of the FRF pier at 36.1872 deg N, 75.7429 W in a depth of approximately 8 m were used for model comparisons. The gauge array provides high-resolution directional measurements. Wave spectra are based on 8192-sec time series of data collected at 2 Hz and analyzed using the Iterative Maximum Likelihood Method (Long and Oltman-Shay 1991, Long and Atmadja 1994). Spectral information is available every 3 hrs starting a 1 hr GMT. Note that the measurements lag 1 hr from the WIS standard output times.

Table 2 provides error statistics for the STWAVE simulations based on the 8-m array measurements. The bias and RMS error are defined by Equations 1 and 2, respectively. Positive biases represent underestimates by the model. The statistics cover the full years, less 20 3-hr measurement gaps in the 8-m array data for 1997 and 15 gaps in 1998. In general, wave height is represented with similar accuracy with the parametric and spectral methods. Wave periods and mean wave directions show significant improvement using the spectral method. Figures 1-4 show comparisons of the measured and modeled wave heights and mean directions for April 1997 and October1998. One-month plots are selected because full-year plots are too compressed to show the details of the comparisons. These two months were shown because they include events with the largest errors in the model results, which will be discussed in more detail in later sections. A wave direction of 70 deg is normal to the shoreline.

**Table 2. Wave model errors based on FRF 8-m array measurements**

| Year | Method | Wave Height | | Peak Wave Period | | Mean Direction | |
|---|---|---|---|---|---|---|---|
| | | Bias (m) | RMS Error (m) | Bias (sec) | RMS Error (sec) | Bias (deg) | RMS Error (deg) |
| 1997 | Parametric | 0.17 | 0.40 | 3.0 | 4.5 | 3.2 | 32.1 |
| | Spectral | 0.14 | 0.37 | 0.6 | 3.8 | 1.8 | 23.3 |
| 1998 | Parametric | 0.18 | 0.44 | 3.7 | 4.9 | 3.3 | 35.7 |
| | Spectral | 0.17 | 0.34 | 1.2 | 3.4 | 2.3 | 22.8 |

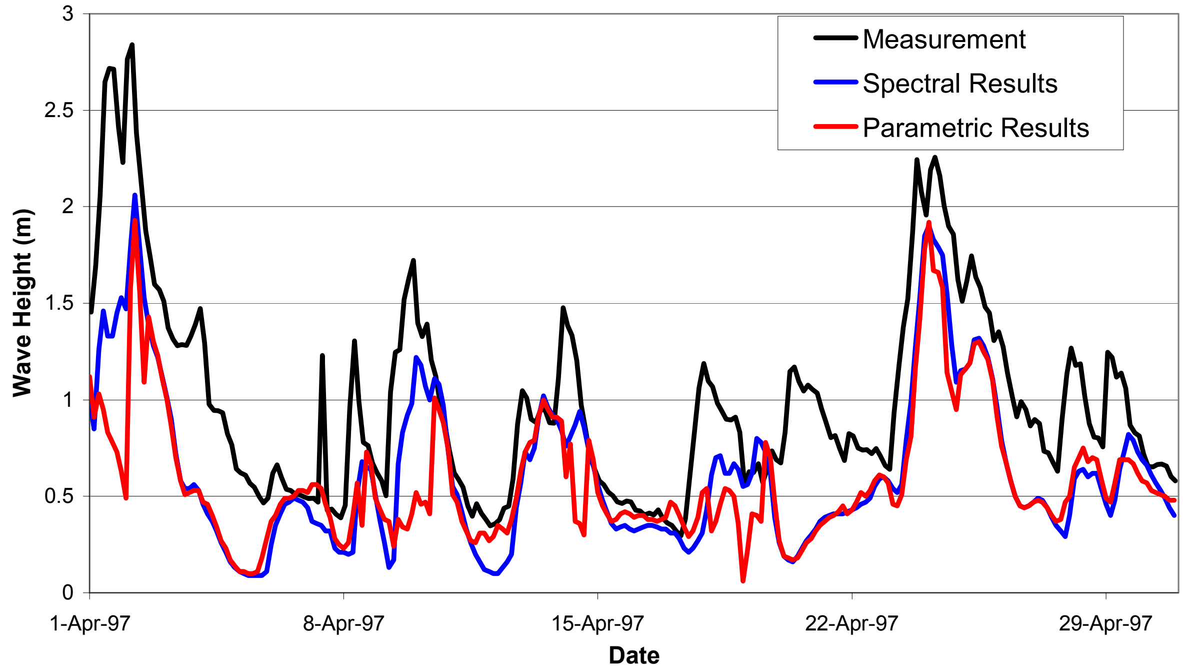


**Figure 1. Comparison of measured and modeled wave height for April 1997 at 8-m depth**

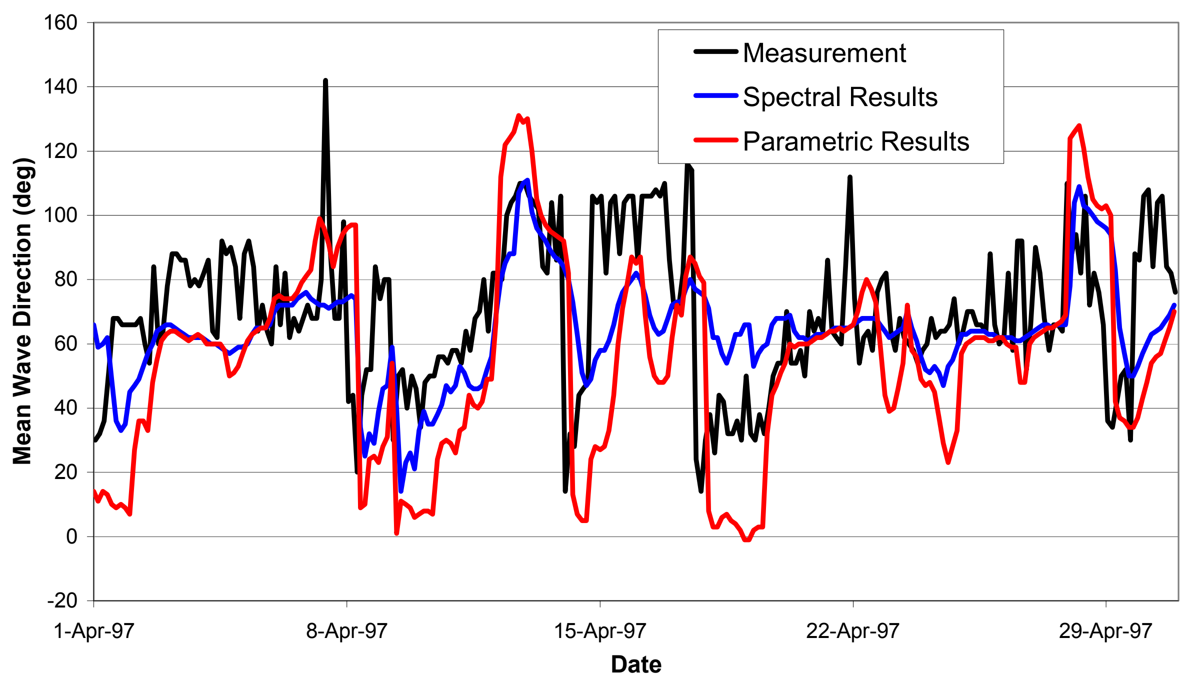


**Figure 2. Comparison of measured and modeled mean wave direction for April 1997 at 8-m depth**

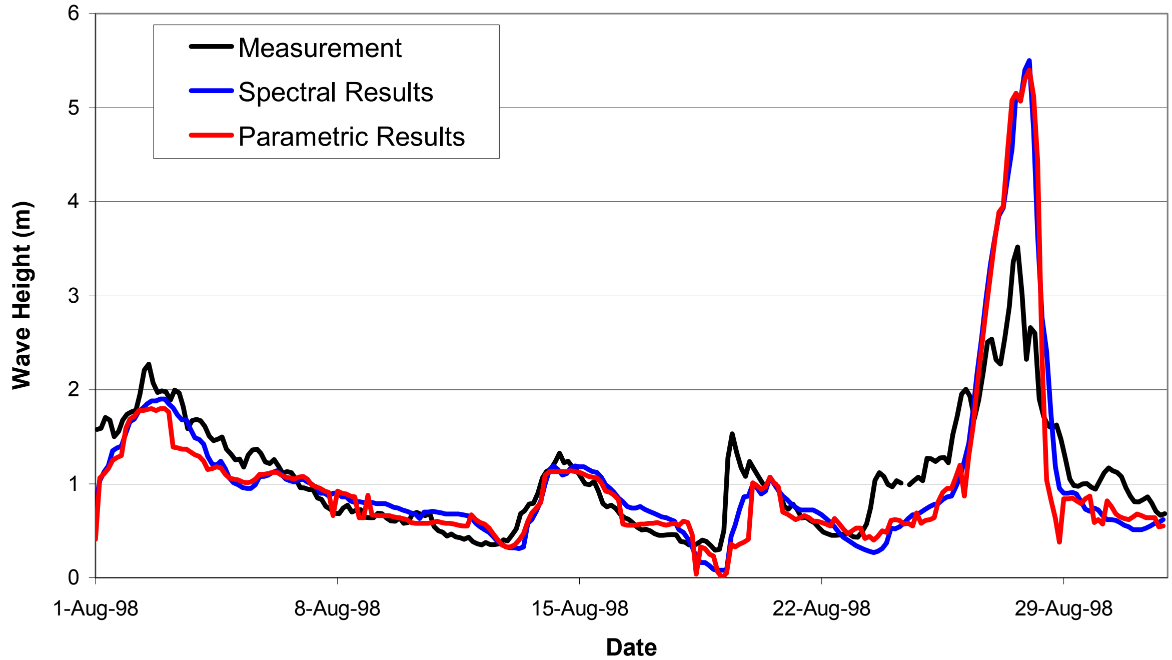


**Figure 3. Comparison of measured and modeled wave height for August 1998 at 8-m depth**

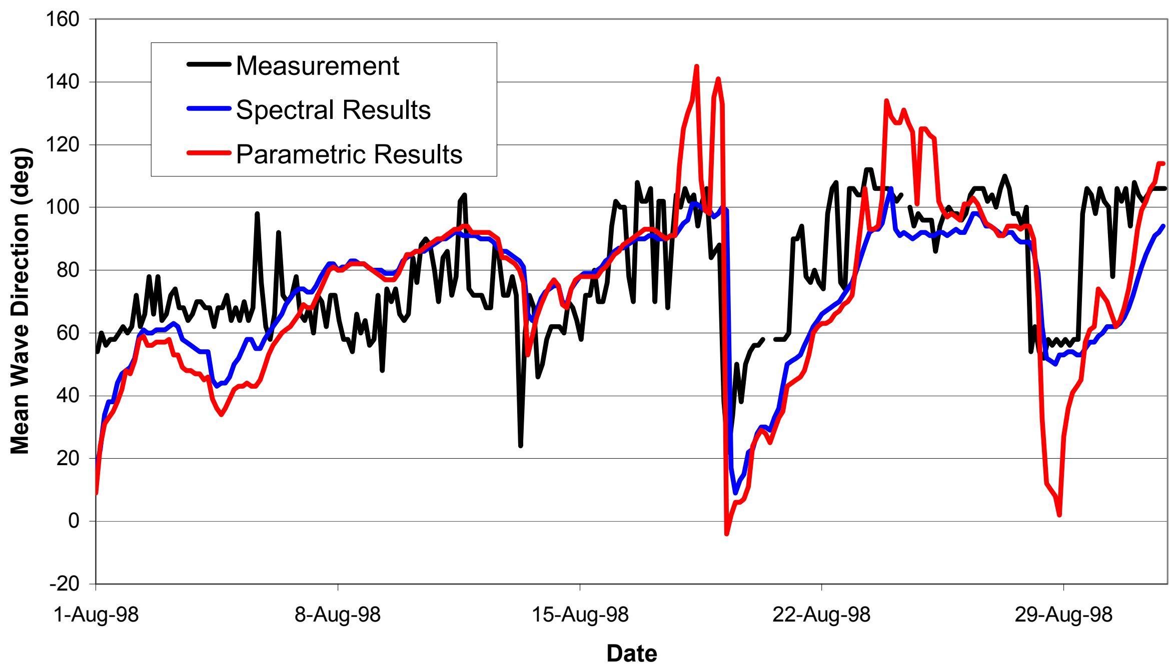


**Figure 4. Comparison of measured and modeled mean wave direction for August 1998 at 8-m depth**

Figures 1 and 3 show that waves heights from the STWAVE spectral and parametric results are very consistent with a few larger errors in the parametric results for isolated points (e.g., 1-2 April 1997). The simulated wave heights (spectral and parametric) are generally smaller than the measurements with the exception of the large overestimate of wave heights during Hurricane Bonnie in August of 1998 (simulated wave height of 5.2 m and measured wave height of 3.5 m). The overestimation during Bonnie is also observed in WIS comparisons to Buoy 44014 (30% overestimate). The larger errors in peak wave period for the parametric results are due to the presence of multiple wave trains that are not modeled with the parametric approach (all energy is assigned to a single peak). Errors in mean direction are reduced by approximately one-third by using the spectral approach. The mean directions from the parametric approach display some large deviations from the measurements and from the spectral approach (20-60 deg). These errors are the result of multiple wave trains or offshore (WIS) peak directions that are nearly parallel to the coast.

## 4. SEDIMENT TRANSPORT CALCULATIONS

The result of interest for most coastal processes investigations is not the waves, but the sediment transport generated by breaking waves. The STWAVE simulations are not of sufficient spatial resolution to determine breaking wave parameters for longshore sediment transport calculations. To estimate longshore energy flux at incipient breaking, STWAVE spectra from the 8-m depth (8-m array location) were linearly refracted and shoaled across a typical one-dimensional beach profile. Wave breaking was implemented using the dissipation function of Battjes and Janssen (1978),

$$D = 0.25 Q_b f_m (H_{\max})^2 \tag{4}$$

$$H_{\max} = 0.14 L \tanh(kd) \tag{5}$$

where

$D$ = energy dissipation
$Q_b$ = percentage of waves breaking based on a truncated Rayleigh distribution of wave heights
$f_m$ = mean frequency
$L$ = wavelength
$k$ = wave number
$d$ = water depth

A single typical beach profile was used for the full 2 years (Figure 5). The longshore energy flux, $P_{ls}$, was calculated based on the Shore Protection Manual (1984) by integration over the spectrum as

$$P_{ls} = \rho g \iint C_g E df \sin 2\alpha d\alpha \tag{6}$$

where

$\rho$ = mass density of water (1000 kg/m$^3$, fresh water)
$g$ = acceleration of gravity (9.81 m/s$^2$)
$C_g$ = wave group celerity

The energy flux was calculated at incipient breaking, as defined by the most seaward location where $Q_b = 0.01$ (or where 1% of the waves are breaking). This is approximately the location where the wave height is largest.

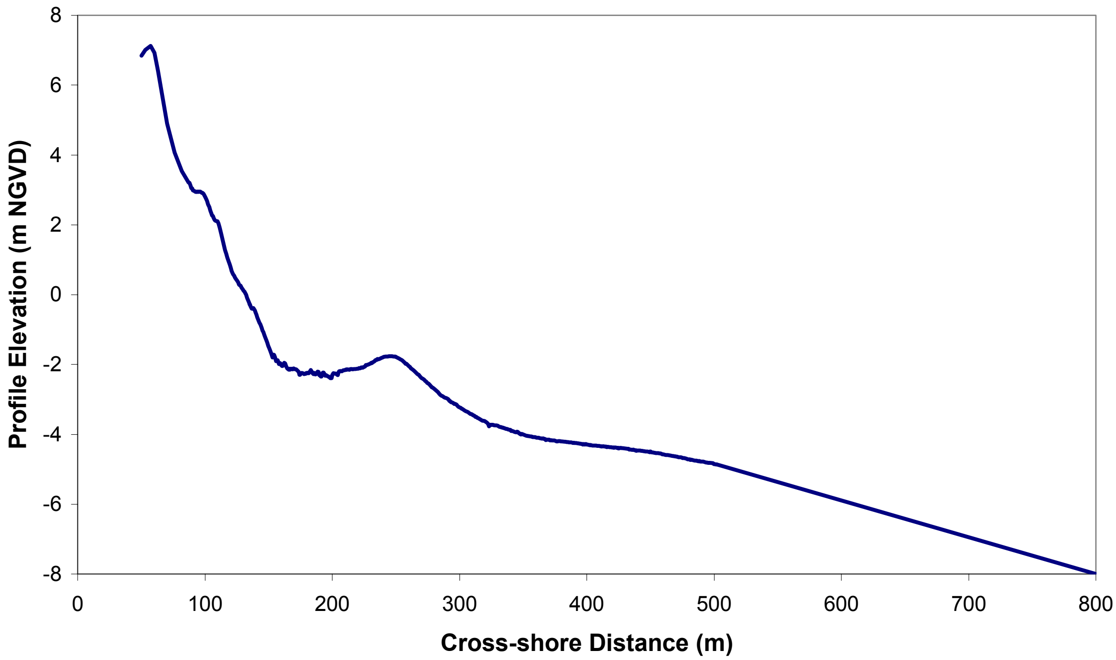


**Figure 5. Typical beach profile used for breaking wave energy flux calculation**

The longshore sediment transport rate ($Q$, $m^3$/sec) is calculated (SPM 1984, Equation 4-49)

$$Q = \frac{0.77 P_{ls}}{g(\rho_s - \rho)(1-n)} \qquad (7)$$

where

$\rho_s$ = mass density of sediment (2650 kg/$m^3$ for quartz sand)
$n$ = sediment porosity (0.4)

The transport rate was calculated for each 3-hr wave condition. The bias and RMS errors for the longshore sediment transport rate are given in Table 3. The larger errors for 1998 are driven by the substantial overestimate of wave heights associated with Hurricane Bonnie. The transport rates were integrated over each 3-hour wave condition to give the cumulative net volume of sediment transport. Figures 6 and 7 shows the cumulative transport for the two wave model results and calculated from the 8-m array measurements for 1997 and 1998, respectively. Positive transport is to the south and negative transport is to the north. The cumulative transport plots show that most of the transport occurs over relatively short events when the wave height exceeds approximately 2 m. These events show up as step functions in Figures 6 and 7. In general, the spectral results provide improved estimates of the cumulative sediment transport (e.g., 25% error in the cumulative transport for 1997 for the spectral results versus 48% error for the parametric results). However, the large overestimate of northward transport associated with Hurricane Bonnie results in cumulative volumes in 1998 for both the spectral and parametric models that are in the wrong transport direction (north instead of south). The cumulative volumes from the spectral method are reasonable for 1998 up to Hurricane Bonnie in late August.

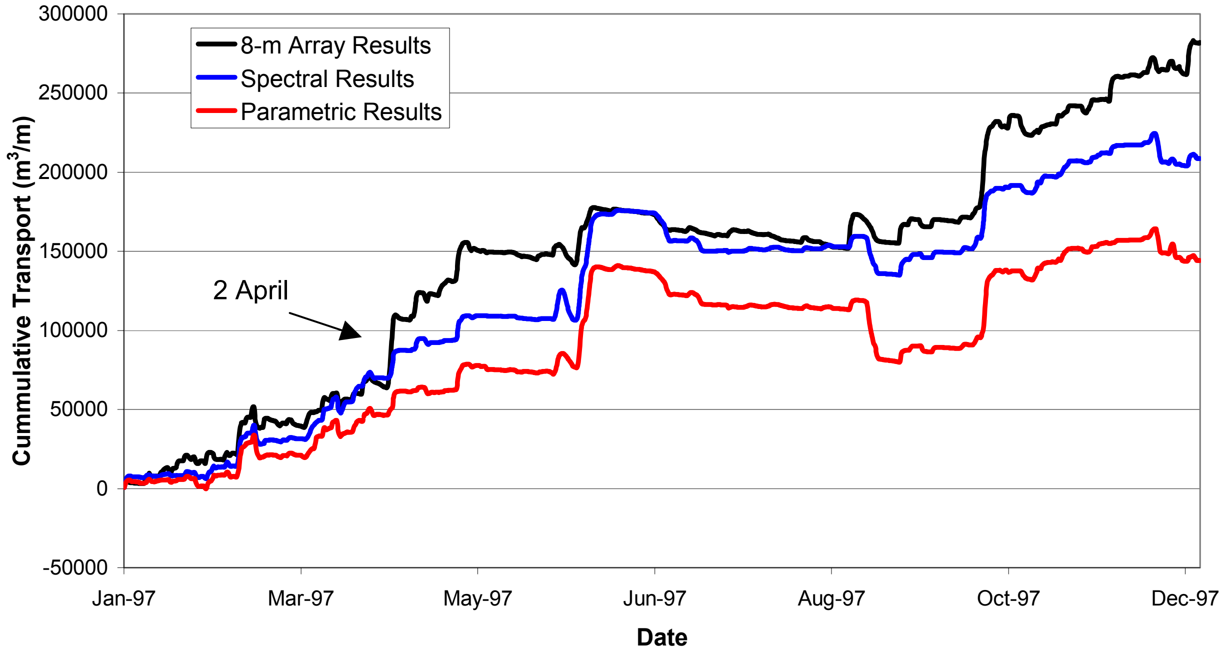


**Figure 6. Cumulative longshore sediment transport for 1997 using spectral and parametric forcing**

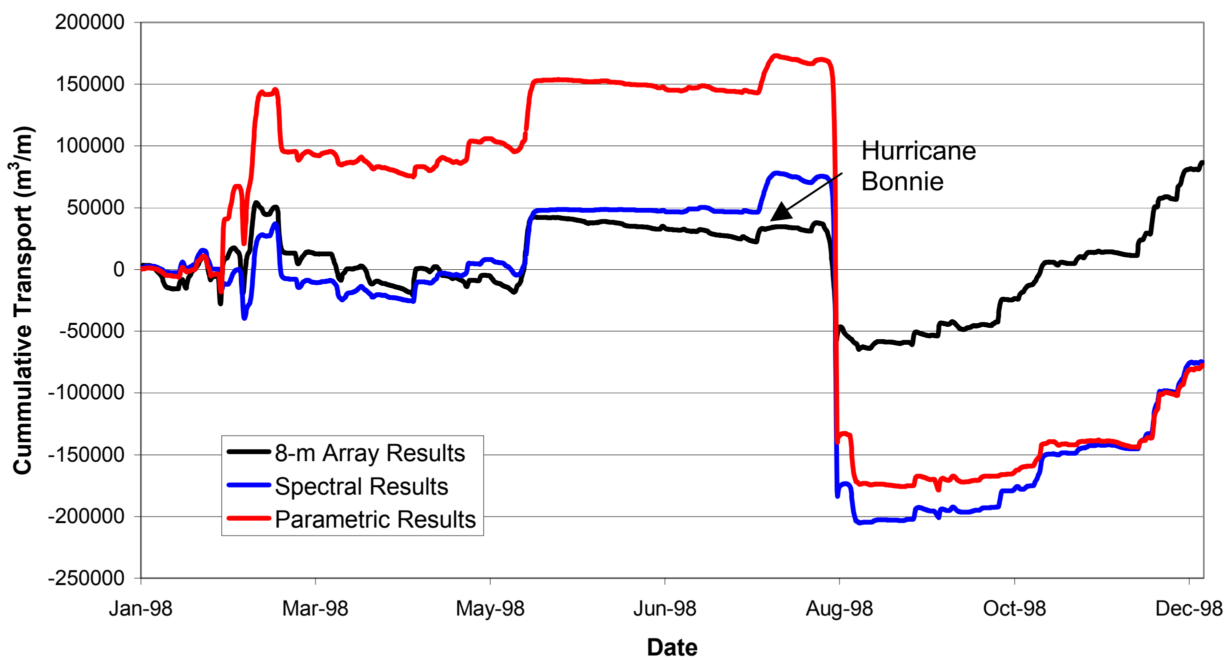


**Figure 7. Cumulative longshore sediment transport for 1998 using spectral and parametric forcing**

| Table 3. Sediment transport estimate errors based on FRF 8-m array measurements | | | |
|---|---|---|---|
| Year | Method | Sediment Transport Rate | |
| | | Bias ($m^3$/sec) | RMS Error ($m^3$/sec) |
| 1997 | Parametric | 47.6 | 478 |
| | Spectral | 25.4 | 437 |
| 1998 | Parametric | 56.5 | 1728 |
| | Spectral | 55.7 | 1350 |

## 5. DISCUSSION

Use of the WIS hindcast wave spectra to drive the nearshore wave transformation model STWAVE provides improved results compared to using bulk parameters of wave height, peak period, and mean direction. For 1997, the bias in transport rate was cut in half using the spectral method. Although the wave height errors are similar for both the spectral and parametric methods, the errors in peak period and, more importantly, mean direction are reduced by approximately one-third. Wave direction is a key element in the calculation of longshore energy flux.

The main difficulty in application of the parametric method is that it over simplifies the energy distribution with direction. An extreme example of this is shown in Figures 8 and 9 for comparisons of the frequency spectra and dimensionless directional distributions, respectively, for the 8-m measurement and the two simulation results. In this case, two spectral peaks were present at 25-m depth (a high-frequency peak that was oblique to shore and a low-frequency peak that was more normal to the shore). In the truncation of the input spectra and the transformation to shore, the higher frequency peak is nearly eradicated and the lower frequency peak dominates. This can generate large errors in total energy, peak period, mean direction, and longshore transport volume (see Figure 6). The key error in the parametric approach is the specification of the mean wave direction. As noted previously, errors in wave height are similar to the spectral approach, but occasional large errors occur in mean direction (20-60 deg). The parametric approach used here could be improved by truncating the WIS spectra to a half plane prior to calculating the wave parameters or by identifying individual wave trains and transforming them independently. These independent wave trains need to be recombined prior to calculating wave breaking.

Parametric approaches to nearshore wave transformation have been used to reduce computational time. Wave parameters are used to generate a wave climate. Then, representative wave parameters are chosen for transformation instead of simulating a full year or multiple years. The nearshore time series of waves/sediment transport are then reconstructed by matching offshore time histories to nearshore model output. This approach requires approximately two orders of magnitude less computation effort than running a full-year time history at 3-hr intervals. Parallel processing now allows us to run simulations with quick turnaround. A one-year simulation for the 16 by 26 km grid used for the FRF took 3.2 hours on an Origin 3000 using 16 processors (or approximately 6 days on a single processor, 400-MHz Alpha workstation). Computational time could be significantly decreased by applying a sediment transport threshold (e.g., Gravens et al. 1991) and eliminating wave events that produce insignificant transport.

Errors in the nearshore wave results come from two sources: input to the model and the model itself. Input error may include errors in the WIS hindcast (e.g., overestimate of wave height for Hurricane Bonnie), local winds, and bathymetry. The comprehensive verification effort for the updated hindcast will help identify WIS errors. Errors within STWAVE may include the truncation to a half plane, linear transformation, and local generation. These potential errors are being further investigated.

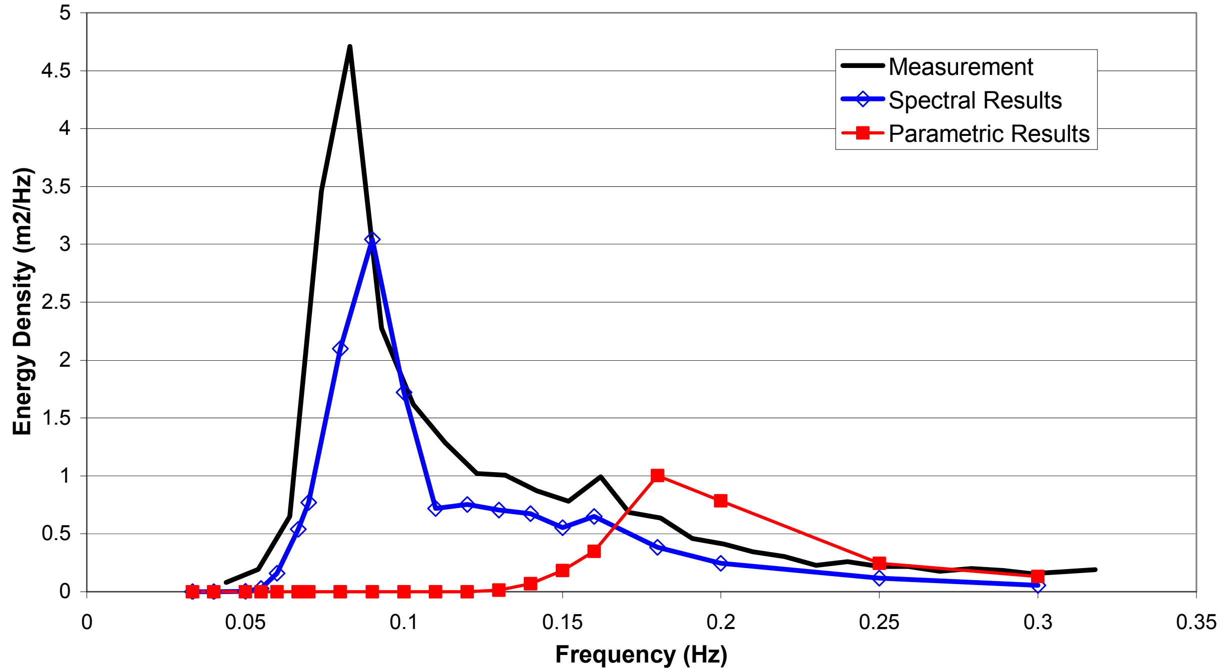


**Figure 8. Frequency spectra from 2 April 1997 at 12:00 GMT**

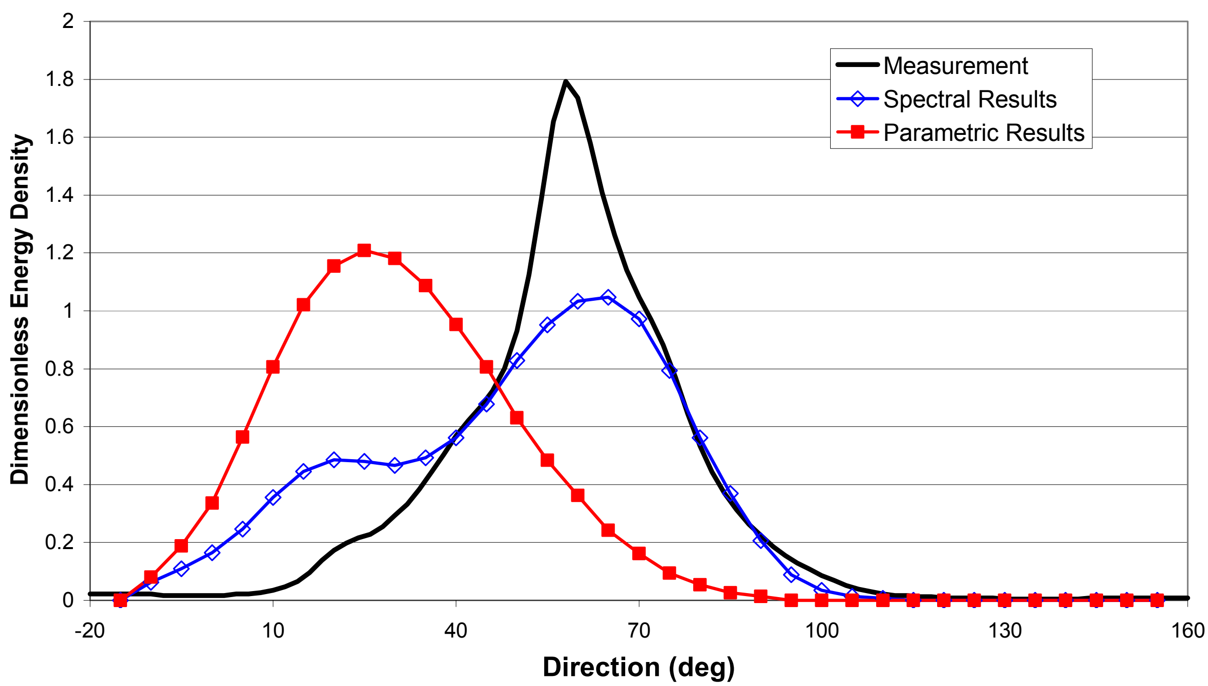


**Figure 9. Directional distribution from 2 April 1997 at 12:00 GMT**

## 6. CONCLUSIONS

This study shows that transformation of the WIS hindcast spectra using STWAVE provides improved results over driving STWAVE using parametric spectra based on the bulk parameters of wave height, peak period, and mean direction. Error statistics show marginal improvement in the modeled nearshore wave height, but significant improvement in peak period and mean direction. The wave energy and direction are the key parameters for estimating longshore energy flux and longshore sediment transport. These improvements come at the cost of increased computation effort. Longshore transport is driven by large wave events, so errors in the STWAVE input conditions for a single large wave event, such as Hurricane Bonnie in August of 1998, can dominate the estimate of cumulative transport over a full year. Thus, good understanding of the error characteristics of the WIS hindcast is critical for application of the data to drive nearshore wave transformation. Use of hindcast (or measured) frequency-direction spectral to drive nearshore transformation preserves the complexity of the wave field (frequency and directional distributions, including multiple wave trains) and improves estimates of potential longshore sediment transport.

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