Model Predictions of Nearshore Processes near Complex Bathymetry

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Abstract*-Waves undergo significant transformation over complex bathymetry, and the resulting nearshore wave conditions can be sensitive to small changes in the offshore wave forcing. A potential consequence of this transformation sensitivity is large uncertainties in modeled nearshore waves owing to the amplification of the error in the deep water spectra used as initial conditions. In preparation for the upcoming Nearshore Canyon Wave Experiment in La Jolla, CA, a boundary condition sensitivity analysis was performed over the region's submarine canyon bathymetry using the SWAN wave model The sensitivity analysis included varying the offshore spectrum discretization (frequency and directional bandwidths), the peak period and direction of the spectra, and the frequency and directional spreads. In each case, the magnitude of the spectral variations was governed by the expected uncertainties when initializing a nearshore model with a) typical buoy data for the area, and b) global WAM model hindcasts or forecasts. In addition, data from the Torrey Pines Outer Buoy (located 12 *km* offshore) from the first week of November 2001 wereused to initialize the model, and the maximum change seen in the domain over the course of the week were compared to those derived from the sensitivity analysis.The nearshore locations that showed the largest change in wave height over time were also the areas most sensitive to boundary condition errors, and correspond to areas of wave focusing. Errors in the estimation of the peak offshore wave direction were found to have the greatest impact on the accuracy of the nearshore wave predictions.The coarse directional resolution (15 degrees) of deep water spectra provided by the present generation of operational global models is shown to be a significant source of error when hindcasting or forecasting nearshore waves over complex bathymetry.

I. INTRODUCTION

As ocean waves propagate from deep to shallow water, they become increasingly influenced by the underlying bathymetry. In areas where the bathymetry is complex, wave characteristics in the nearshore areas (including the shoaling and surf zones) are highly sensitive to variations in the incident offshore wave conditions. A tightly focused, narrow banded wave train may transform over complex bathymetry into waves moving in opposing directions, relative to the beach normal, which in turn would generate rip current fields. The location and occurrence of these rip current fields are strongly dependent on the nature of the offshore waves.

Submarine canyons are an excellent example of complex bathymetry. Refraction theory shows that wave energy is defocused in the embayments at the canyon heads and strongly focused at the headlands near the edges of the canyon. If the canyon were relatively long and narrow, the region of low or high waves caused by refraction only extends over a short stretch of coastline, resulting in a large alongshore wave energy gradient. This variability is also strongly dependent on the offshore wave environment.

The sensitivity of nearshore processes to the offshore wave climate becomes a concern when developing a modeling system for the area. Initial conditions, whether in the form of buoy data or input from a forecast model, must be chosen such that sufficient spectral detail is captured without requiring prohibitively-expensive computation. For most open-coast situations over near-straight, near-planar bathymetry, this issue is not a significant concern. However, for areas in which complex bathymetry dramatically transforms the propagating wavefield, this problem becomes paramount. This is particularly true when using initial conditions from a larger scale model forecast, which may be more suited to open ocean wave propagation than as input for nearshore predictions.

In section II, we describe the geographic setting of the Scripps and La Jolla submarine canyons and the wave climatology of the region. An overview of the wave models and buoy measurements typically used to predict wave spectra in deep water, offshore of the canyons, are presented in sections III and IV, and nearshore wave models are described in section V. Changes in the nearshore waves owing to small variations in the offshore wave spectra are quantified in section VI, and the conclusions from this sensitivity analysis are presented in section VII.

II. THE NEARSHORE CANYON EXPERIMENT (NCEX)

The Nearshore Canyon Experiment (NCEX), slated for the fall of 2003, is intended to measure nearshore waves, currents, sediment transport, and other phenomena near an area of complex bathymetry. The experiment will be held near Scripps Institution of Oceanography in La Jolla, CA. The institution is situated between two large undersea canyons (Figure 1) with the experiment focusing on the northern Scripps Canyon near Black's Beach, a location well known to surfers for it large and complex-shaped surf break. Scripps canyon is deep and narrow, less than 200 meters wide just seaward of the two-branched canyon head, with nearly vertical canyon walls. Figure 1 shows the bathymetric contours of the area, with significant wave height predictions from the SWAN model [1] superimposed. The higher waves (red) at Black's Beach are a persistent feature. The strong variation in waveheight along the coastline from Scripps Canyon to Black's Beach is clearly visible in the figure.

The wave climate near La Jolla is relatively benign for most of the year, and is characterized by afternoon sea breeze-generated local seas superimposed on larger, low frequency swells arriving from distant North Pacific and Southern Ocean storms. During the summer months, southern ocean storms are the source of most low frequency swells which travel great distances to arrive at the California coast. The only noticeable blocking of the swell prior to reaching the islands in the Southern California Bight is by small island chains in the Pacific (e.g., Hawaiian Islands, French Polynesia.). Southern swell rarely exceed 2m significant wave heights in deep water off California, however, their long periods and narrow frequency and directional distributions can lead to strong refraction and shoaling effects in shallow water. During the winter months, most of the swell arrives from the North Pacific storms. Swell arriving from northern directions tend to be equally narrow in directional spread compared to southern swell, owing to the blocking of the nearby islands in the Southern California Bight. However, the frequency spread of northerly swell tends to be greater than south swells because they travel a shorter distance resulting in less frequency dispersion of the swell energy. North Pacific swell are often much larger than south swell off La Jolla, despite the local island blocking, with the larger events exceeding 5m water significant wave heights in deep water, resulting in enormous breaking waves adjacent to the canyon heads in shallow water.

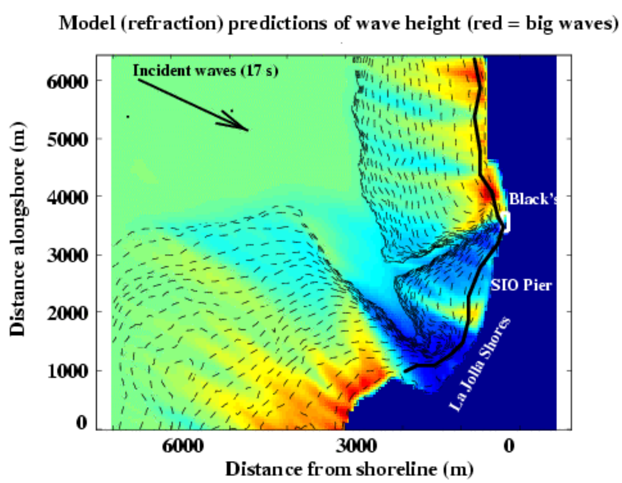

Figure 1. Domain of Nearshore Canyon Experiment. Scripps Canyon is the northernmost canyon, with Black's Beach further north. Bathymetric contours denoted in black dashed lines. Colors are of significant waveheight from SWAN model; red indicates regions of high waves (about 2.5 times the offshore waveheight).

III. CHARACTERISTICS OF FORECASTING MODELS FOR OFFSHORE WAVE CONDITIONS

The forecasting of wave conditions for this area involves obtaining offshore conditions from a wave forecasting model. Several operational forecasting centers run the WAM model [2] on a global scale, though the WAVEWATCH-III model [3] is playing an incrementally larger role in global wave prediction. The operating parameters for these models are based on turnaround time; Naval operational centers in the U.S. (Naval Oceanographic Office, Fleet Numerical Meteorological and Oceanographic Center) provide 96 –hour forecasts twice daily, involving much computational time. The usual global grid resolution is 1° latitude and longitude, which is too coarse to resolve Pacific island groups [4]. These models typically use a logarithmic frequency distribution, with fine resolution for the low-frequency swell and coarser resolution for the higher-frequency wind sea. Directional resolution of most operational runs is 15°, sufficient resolution for representing the dynamic aspects of the model (energy sources, sinks and redistribution due to wind, dissipation and nonlinear interactions) but potentially problematic for capturing the kinematics of long propagation distances [4].

Recently, the Navy Swell Model was developed and put into experimental operational use at the Naval Research Laboratory. This model propagates wave rays backwards from a point of interest using swell propagation theory along great circle paths; the propagation characteristics are therefore exact and not dependent on numerical discretization characteristics. There are no source/sink terms internal to the model; WAM global source/sink terms are used to represent wave generation and dissipation, and resulting swell propagated along these ray paths. Because of the relative computational expedience of this modeling system, a finer global grid of 5 minutes can be used, thus adequately resolving islands that may affect global wave propagation. One disadvantage is the dependence on WAM for source and sink information. The WAM model is not corrected by the swell model, so errors in the propagation from WAM before the swell model intercepts it affects the accuracy, though the swell model would still mitigate these propagation errors [4].

IV. WAVE MEASUREMENTS

The Coastal Data Information Program (CDIP), funded by the State of California and the U.S. Army Corps of Engineers, has deployed directional wave buoys at numerous locations along the California coast. These buoys are typically placed in deep water, at the edge of the continental shelf, and are used to initialize regional wave propagation models to wave nowcasts or hindcasts for the coast [5]. A Datawell Directional Waverider buoy (denoted the Torrey Pines Outer Buoy) is located 12 *km* offshore of Torrey Pines, CA, and will be used for determining offshore conditions for the NCEX domain. The Maximum Entropy Method [5.1] is used to estimate directional spectra with 5° directional resolution and 0.01 *Hz* frequency resolution from 60 minute records of the x, y, and z translation of the surface-following buoy The selection of the frequency and directional resolution of buoy spectra estimates is a tradeoff between spectral resolution and statistical uncertainty. . For a fixed buoy record length and sampling frequency, statistical uncertainty in the estimated spectral components increases with increasing spectral resolution. However, we demonstrate in section VII that too coarse a frequency-directional resolution in the intializing deep water spectra can lead to undesirably large uncertainties in the nearshore wave predictions.

V. MODELS FOR REGIONAL AND NEARSHORE CONDITIONS

While well suited for large scale wave propagation, global scale models such as WAM or WAVEWATCH-III are typically too coarsely resolved to adequately handle bathymetric effects, particularly the relatively rapid variation of wave characteristics imparted by complex bathymetry. Additionally, the larger scale models typically have explicit numerical schemes for geographical propagation; these numerical schemes, while efficient with computer memory, are dependent on the Courant number criterion for their stability. This criterion links the time step with the spatial resolution, thus forcing a potentially extreme reduction in the time step if the spatial resolution were increased to accommodate the variable nature of the nearshore bathymetry. Time-stationary models capable of handling nearshore bathymetry are thus required. Typical regional domains can range from a few kilometers on a side to 300 *km* on a side (the size of the Southern California Bight). If detail is required in smaller areas within the regional domain, further model nesting can be performed.

Typical regional scale models include phase-averaged models such as SWAN [1] and STWAVE [7], both of which have depth limited breaking effects. Though potentially useful for regional scale modeling as well, phase-resolving models such as REF/DIF-1 [8] and REF/DIF-S [9] are usually used at nearshore scales (grid domains of two kilometers on a side or less). These models contain wave diffraction effects, which are potentially important for nearshore areas with isolated features such as shoals. These models also have depth-limited breaking effects in their formulations. Results from these models can be applied as forcing for nearshore hydrodynamic models and sediment transport models.

VII. SENSITIVITY TO ERRORS IN INITIAL CONDITION

A natural concern in simulating processes in this area is the potential effect of errors in specification of the initial condition. Because of the complexity of the canyons, one may expect that these errors may amplify in the nearshore. We analyze this effect by running the SWAN model over the area and changing various parameters of the offshore spectrum slightly (with a fixed frequency-direction discretization). We then calculate the difference in significant wave heights (expressed as percentage change) over the domain between the two closely related runs, with special attention paid to the nearshore area by Scripps Canyon and Black's Beach. . The area (Figure 1)is approximately 7 *km* by 6 *km*, with a grid spatial resolution of dx=77 *m* and dy=93 *m.* It is believed that this resolution is sufficient to allow accurate representation of the large-scale features of the bathymetry that refract swell.

Errors in the offshore conditions can be represented in several ways:

1) Errors in the peak direction
2) Errors in the peak period
3) Errors in estimation of the directional spread
4) Errors in estimation of the frequency spread (spectral width)

These errors may be present in either buoy data or global model input; for the purposes of this section of the study we use parameterized spectra to initialize the model, changing the parameters by various amounts. The frequency spectrum is specified by a JONSWAP spectrum [10], which is a function of, among other parameters, the narrowness parameter γ. High values of γ correspond to narrow banded spectra. The directional distribution is specified by a cosine function [11], the narrowness of which is controlled by the spreading parameter σ (in degrees), the one-sided directional width of the directional spectrum; low values of σ imply narrow directional distributions. The analyses encompass a range of initial conditions; however, we will concentrate on a subset of the more interesting simulations in this paper. The offshore significant waveheight, for all runs using parameterized spectra, is 1 *m*.

We first analyze the effects of errors in the estimation of peak direction. Since swell is a particular concern, we concentrate on longer wave periods (peak period T_p=16 or 18*s*) and narrow frequency and directional distributions. We also assume that either a directional buoy (0.01*Hz* frequency resolution, 5° directional resolution), or a numerical model such as WAM (variable frequency resolution, 15° directional resolution) provide initial conditions. Since the resolution of the SWAN model is finite, one can consider boundary condition change of the peak frequency or angle smaller than the SWAN spectral discretization bandwidth as being undetectable. Were the peak direction to be, for example, 291° rather than 290°, neither the estimated buoy spectra nor the numerical models would resolve this difference.

For simulating uncertainty from the buoy data, we initialize the model with the primary direction coming from both 290° and 292.5°. This represents half the 5° directional band of the buoy data, and is an indication of the potential directional error in using 5° bins. Figure 2 shows an example with T_p=18*s*; though waveheights in the nearshore can vary as much as 25 percent with a 2.5° change in initial direction, the variations at the NCEX experiment sites are considerably lower (~5 percent).

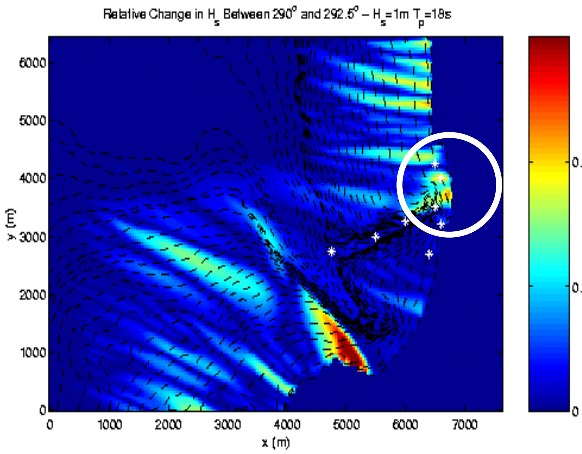

Figure 2. Variation in significant waveheight between initial peak directions of 290° and 292.5°. Nearshore areas of interest circled.

We repeat the analyses, this time assuming data are obtained from the global WAM model (15° directional resolution, with a maximum uncertainty of 7.5°). Figure 3 shows the results. The area of the NCEX experiments evidences a much higher variability in waveheight (upwards of 25 percent) with a 7.5° uncertainty in initial angle, indicating that finer angular resolution is required from forecast models to reduce the sensitivity to unresolved angles of incidence and, consequently, reduce the error.

Next, we study the effects of errors in estimation of the peak period. We limit ourselves here to the buoy data, which has a frequency discretization of 0.01 *Hz*, and thus wave frequencies within 0.005*Hz* of the bin-centered frequency are unresolved. Again concentrating on T_p=18 *s* and a peak direction of 290°, an error of 0.005 *Hz* on either side of the peak period implies possible alternative peak periods ranging between T_p=16.5 *s* and 19.8 *s*. Figure 4 shows the result for the difference in waveheight fields between T_p=18 *s* and 19.8 *s*. While the probable error in significant waveheight can reach 30%, the maximum error at the nearshore locations of the experiment never rises above ~12%. Errors are lower for an initial T_p=16 *s* (not shown). We note here that, because of WAM's logarithmic frequency mapping, the frequency discretization near the peak period of T_p=18 *s* is somewhat finer than 0.01 *Hz*.

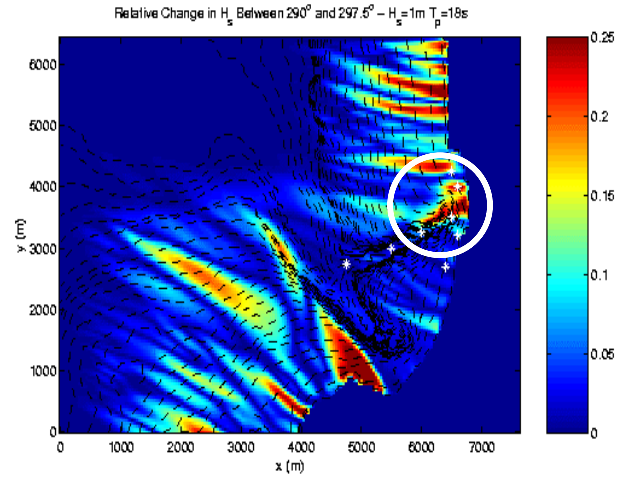

Figure 3. Variation in significant waveheight between initial peak directions of 290° and 297.5°. Nearshore areas of interest circled.

We then investigate the effect of errors in estimates of the directional spread σ. Retaining the primary spectral parameters we have assumed as a proxy for swell (T_p=18 *s*, peak direction of 290°, and γ=20) we used values of σ = 5°, 7.5° and 10°, looking at the difference in the resulting waveheights between each neighboring pair. Figure 5 shows the waveheight difference between σ = 5° and 7.5°.

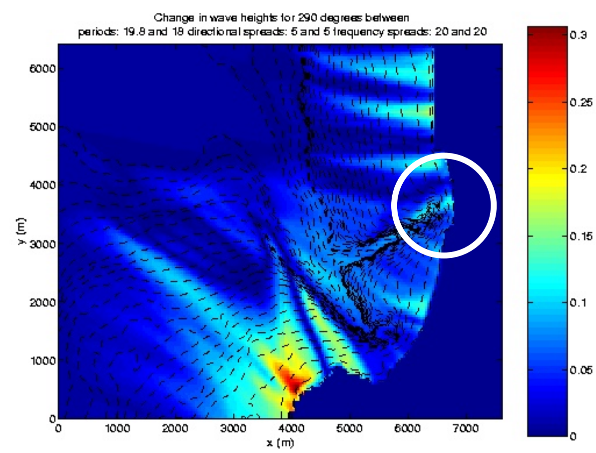

Figure 4. Variation in significant waveheight between initial peak periods of 18 and 19.8 *s*. Nearshore areas of interest circled.

Interestingly, errors due to misidentification of the directional spread seemed to be lower than those resulting from errors in the peak. One possible reason is that the directional spreads used here are lower than those used to analyze the peak direction. Wider directional distributions tend to diffuse the focusing and attenuation effects of complex bathymetry, and thus the sensitivity to errors in estimation of the directional characteristics of spectra are reduced.

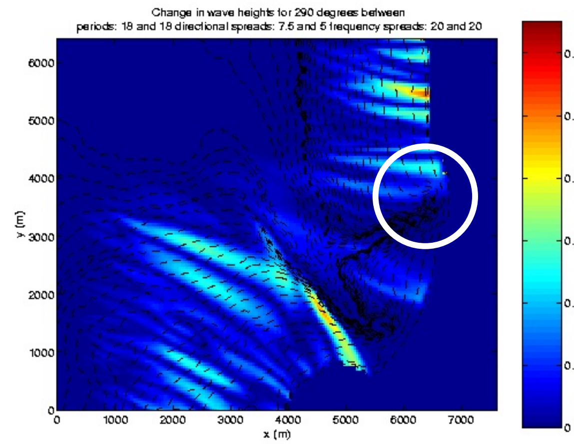

Figure 5. Variation in significant waveheight between directional spreads σ= 5° and 7.5°. Nearshore areas of interest circled.

Finally, we analyzed the effect of errors in estimation of the frequency spread. Fewer assumptions are involved with estimation of frequency spectra than directional spectra from buoy measurements, so errors in this estimation are less likely to occur. Nevertheless, this analysis does lend insight into the sensitivity of the variability of the wavefield to changes in spectral width, particularly over complex bathymetry. For this analysis we retained the same wave parameters as before, but used a directional spread σ=5° and varied the frequency spread γ between 15 and 20. Figure 6 shows the result; there appears to be an order of magnitude less variation due to frequency spread errors than peak frequency identification errors (Figure 4).

VI. MEASURED CONDITIONS DURING 1-8 NOVEMBER – SENSITIVITY ANALYSIS

While the use of synthetic initial conditions is useful as a general test of model sensitivity, we wanted to insure the findings were relevant for the upcoming NCEX field experiment. We isolated a week of Torrey Pines buoy data (1-8 November 2001), during which low frequency swell was propagating from the north and is representive of the conditions expected during the NCEX experiment. The data consisted of hourly directional spectra from the buoy. Peak periods for the spectra remained in the T_p=12-15*s* range for most of the time period. Significant waveheights ranged from 0.7-1.3*m*, while incident direction for most of the study period remained close to 285°. Each directional spectrum was run through the SWAN model and significant waveheight over the domain calculated.

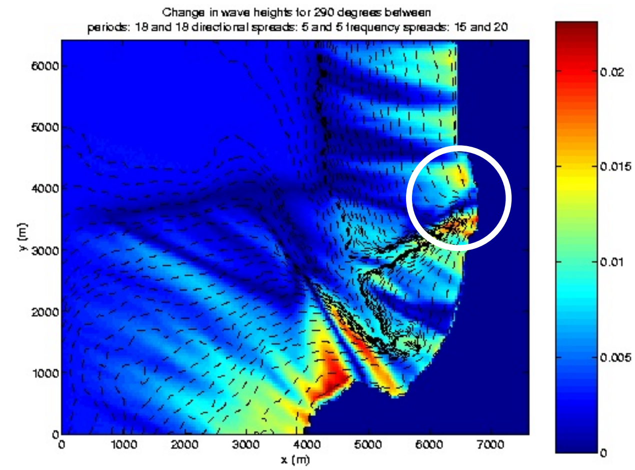

Figure 6. Variation in significant waveheight between frequency spreads of γ=15 and 20. Nearshore areas of interest circled.

We wished to see which areas of the NCEX domain underwent the most change in significant waveheight over the course of the week due primarily to changes in peak period and direction. We first normalized all significant waveheight fields by the offshore significant waveheight. We then calculated the change in normalized waveheight from one hour to the next at every point in the domain, and retained the maximum change, resulting in Figure 7. Note that the Black's Beach area (just north of Scripps Canyon along the coastline) seems to experience the greatest change in waveheight at the NCEX sites of interest.

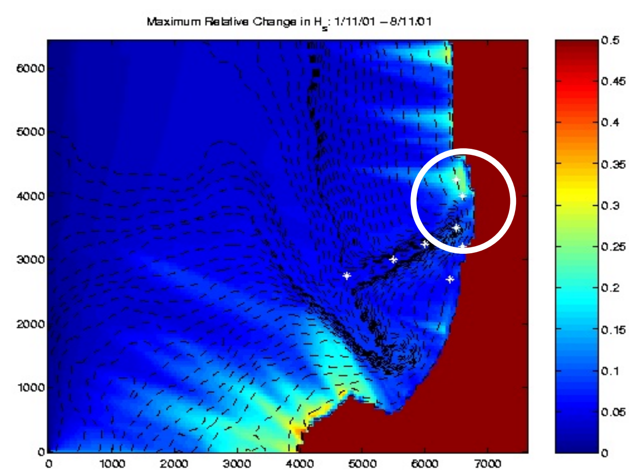

Figure 7. Areas of maximum normalized change in significant waveheight, 1-8 November 2001.

We inferred spectral parameters (γ, σ) describing spectral width (frequency and directional spread, respectively) from the data, allowing the use of parameterized JONSWAP spectra [10] with parameterized directional spreading [11] for specification of the initial condition in the sensitivity analyses that follow. We did not attempt to find the best-fit values of (γ, σ) for the entire data set, but instead used pre-set increments of (γ, σ) and found the increment which produced minimum error when compared to the data. Based on this, we determined that frequency spreads of γ=1 to 3.3, and directional spreads of σ=5° to 10°, appeared to match most of the data.

Using γ=3.3 and σ=7.5°, we recreate the angle sensitivity study detailed in the previous section (note that γ=20 and σ=5° was used previously). Figure 8 is the result using a 2.5° uncertainty (mimicking field data) and Figure 9 is that using a 7.5° uncertainty (as in WAM spectra).

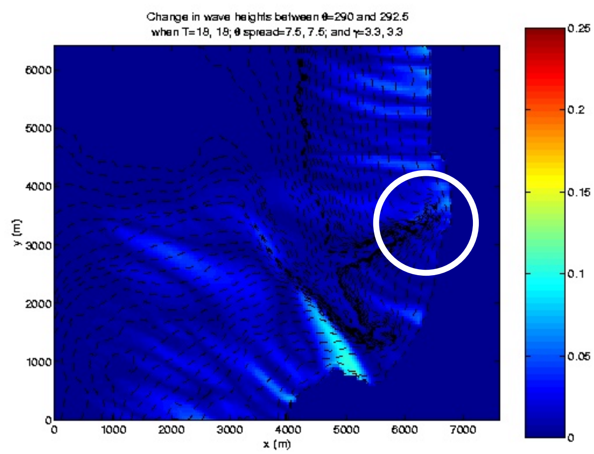

Figure 8. Variation in significant waveheight between initial peak directions of 290° and 292.5°, using frequency and direction spreads derivedfrom data. Nearshore areas of interest circled.

It is evident that the stark contrast in error amplification seen in Figures 2 and 3 is only slightlyreduced with the wider frequency and directional distributions. While the uncertainty in waveheight owing to unresolvable peak directions in the buoy data is less than 7% for the nearshore NCEX sites, it is nearly 15% at Black's Beach when using the WAM model input.

VII. CONCLUSIONS

Waves propagating over complex bathymetry undergo significant transformation, particularly in areas where narrow-banded swell is common. The extreme variability exhibited in the nearshore wave climate indicates a possible high sensitivity to deep water spectral resolution and accuracy when specifyinginitial conditions; and initialization errors will likely have a strong effect on the prediction of nearshore processes, particularly in the areas where strong wave focussing occurs.

We used the SWAN model [1] to study the effect of erroneous initial conditions on the wave predictions in nearshore areas of interest during the NCEX experiment, and simulated buoy measurement uncertainties or global model errors in the initializing spectra by slightly varying the parameters which specify the spectra, then

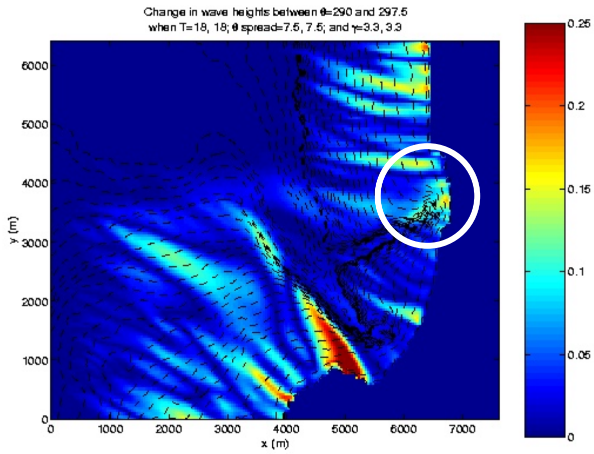

Figure 9. Variation in significant waveheight between initial peak directions of 290° and 297.5°, using frequency and direction spreads derived from data. Nearshore areas of interest circled.

calculating the difference in significant waveheight over the domain resulting from this variation, noting in particular the changes at the nearshore NCEX sites. Errors in the initial peak direction were assumed to have come from two sources - buoy data (5° angular discretization) and a global WAM model (15° angular discretization) – with the errors representing unresolved variations in peak direction within the discrete bands. Errors in the peak period were assumed to have come from statistical uncertainty in buoy frequency spectra (0.01 *Hz* bands) or WAM model swell generation errors. . Errors in frequency and direction spreading were simulated by closely-spaced "typical" parameter values., In each case, the differences in the resulting SWAN waveheight fields were quantified. Errors in the specification of peak direction has the greatest impact on the nearshore wave heights, with the uncertainties resulting from WAM's coarser directional banding being of particular concern.

One week of data from the Torrey Pines buoy when north swell were present (1-8 November 2001) was also used to initialize the model to quantify natural variations in nearshore swell heights at specific sites over time. After normalizing the energy content of the spectra, the maximum change in normalized energy over the domain was examined. The head of Scripps Canyon (relatively low wave heights) did not undergo significant change, while the Black's Beach area underwent ~20% change over the course of the week. Since energy was normalized, this change was owing to variations in the buoy estimated deep water spectra distributions over the week-long span and is consistent with the model sensitivity tests performed with parameterized spectra. This data set is likely representative of conditions which will be present during the NCEX time frame and should provide some guidance to investigators when developing field observation plans to separate physics-driven variations in the nearshore wave field from modeling uncertainties. Finally, we inferred best-fit frequency and direction spreads from the data, and used those values to re-estimate the effect of errors on the initial direction. Though the errors in general were smaller than with the narrow-banded spectra (lower spread than seen in the data), the amplification of error from coarse directional binning is still present.

It is clear that the coarse directional discretization of the global WAM model results in poorly resolved peak wave directions and potentially significant errors in the prediction of the nearshore waves over complex bathymetry. One possible solution is to use the Navy Swell Model to initialize the nearshore models for the NCEX domain. This would require very fine spatial resolution in the Southern California Bight region so that blocking effects from the islands in the region are well represented.

VIII. ACKNOWLEDGMENTS

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