Model Predictions and Sensitivity Analysis of Nearshore Processes over Complex Bathymetry

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1. INTRODUCTION

Ocean wave propagation is strongly affected by the underlying bathymetry, particularly if the bathymetry is complex in plan and/or profile. Refraction patterns from undersea canyons, for example, lead to reduced waveheights in the embayments at the canyon heads and amplification at the headlands at the canyon edges. This degree of longshore variation in the nearshore wave climate can potentially lead to significant nearshore circulation features, including rip currents. Apart from the bathymetry, the nature of the nearshore circulation and the magnitude of the velocities are strongly dependent on the offshore wave climate.

Nearshore processes in areas of complex bathymetry are highly sensitive to variations in the offshore wave climate. These variations can be due to both actual changes in the offshore wavefield and/or difficulties in the measurement or modeling of swell waves. Errors in the estimation of offshore conditions will likely be amplified in the nearshore, particularly if the bathymetry is complex.

2. NEARSHORE CANYON EXPERIMENT (NCEX)

The Nearshore Canyon Experiment (NCEX) will take place during fall 2003 near Scripps Institution of Oceanography in southern California. Wave transformation and nearshore processes near the head of Scripps Canyon and at Black's Beach will be measured. Bathymetry of the area is shown in Figure 1. During this time, most of the swell wave energy arrives from North Pacific storms. In contrast to the well-sorted southern hemisphere swell, the northern swells usually have a wider frequency distribution since they can be the result of both distant and local storms.

To aid in experiment planning and deployment, an ability to forecast wave conditions in the area is desirable. During the experiment, initial conditions for model forecasts can be made available from global wave models (WAM, WAVEWATCH-III), or from the Navy Swell Model, and initial conditions for nowcasts would be available from offshore buoys.

3. GLOBAL WAVE MODELS

Regional and local wave model forecasts for a nearshore area are typically forced by initial conditions from a global scale wave model. Several operational forecast centers run the WAM model (Komen et al., 1994) and/or the WAVEWATCH-III model (Tolman 1998) for global scale forecasts. While the operational parameters chosen for the models ensure optimal turnaround time, they may not be suitable for capturing the physics of the nearshore environment; for example, most operational centers use a directional discretization of 15°, which may obscure the narrow directionality of swell propagation. Furthermore, global grid resolution is 1°, required for operational use but too coarse to resolve many island chains in the Pacific (Hawaii, French Polynesia). Potential blocking of swell by these islands is therefore not represented.

Recently the Naval Research Laboratory (NRL) has made the Navy Swell Model operational on an experimental basis. The model propagates wave rays (at 1° directional resolution), backwards from points of interest to deep water offshore. These wave rays use time of travel to intersect forecasted swells generated by global models and propagate them toward the points of interest. Since the solution is exact, there is no error associated with numerical discretization. Also, because of the relative computational expedience of this modeling system, a finer global grid of 5 minutes can be used, thus resolving smaller land masses which might block swell energy. One disadvantage of the swell model is the reliance on the source terms of the global models, though the exact nature of the propagation may ameliorate some of this difficulty.

4. WAVE MEASUREMENTS

Wave nowcasts and hindcasts can be initialized with wave measurements, which can be obtained from directional wave buoys located offshore. Agencies and programs such as the National Data Buoy Center (NDBC), the Coastal Data Information Program (CDIP) and the Wave-Current Information System (WAVCIS) routinely deploy directional wave buoys. In the case of the NCEX site, a Datawell Directional Waverider buoy (denoted the Torrey Pines Outer Buoy) has been deployed to provide initial conditions for nowcasts. The buoy is located 12 *km* offshore of Torrey Pines, CA. The Maximum Entropy Method (Lygre and Krogstad 1986) 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. Typically, statistical uncertainty in estimation of the spectral components increases with increasing spectral resolution. One of our goals in this study is to analyze the effect of spectral resolution on the certainty of estimating the nearshore wave climate.

5. BATHYMETRY MEASUREMENTS

Prior to 2001, bathymetric data for the NCEX site consisted solely of depth soundings from the National Ocean Service (NOS), which were gridded by O'Reilly and Guza (1993) to create a 3 second by 3 second (77 *m* east-west, 93 *m* north-south) bathymetric map. This bathymetry was shown in Figure 1, and was the basis for prior wave modeling analysis of the NCEX area (Kaihatu et al. 2002a). Recent surveys performed specifically for the experiment have focused on shoreline location and accurate mapping of the head of Scripps Canyon, and were then combined with the earlier NOS data. This bathymetry is shown in Figure 2. A closeup of the head of Scripps Canyon in Figure 4 reveals the difference between the old and new surveys, with the new surveys showing a steeper slope at the head and a narrower planform than seen in the old survey. Additionally, while the canyon head from the NOS survey appeared roughly symmetrical, the new surveys show a small branch at the head pointing roughly north. This feature provides an additional refractive attenuation which reduces the waveheights near Black's Beach, and increases them just southwest of the beach, relative to the old grid. The combined, updated bathymetry set has been compiled and gridded at resolutions as high as 0.15 seconds (~3 *m*) for the entire NCEX area.

To investigate the effects of the updated survey on wave transformation processes near the head of Scripps Canyon, the SWAN wave model (Booij et al. 1999; Rogers et al. 2002) was run with an assumed swell condition (T_p=16s, H_s=1m, q_p=295°) over both the old and new bathymetries. Figure 4 is a contour plot of the percent increase in wave height using the new Scripps Canyon bathymetry, while Figure 5 shows the percent decrease in waveheight with the new bathymetry. South of the canyon, waveheights are increased with the new bathymetry; the steeper side slopes and narrower planform of the canyon in the new bathymetry increases the refraction toward the sides relative to the old bathymetry. Additionally, waveheights just offshore of Black's Beach (between x=9500m and x=10000m, and between y=6000m and y=6500m in Figure 4) are also amplified with the new bathymetry. This latter feature is likely due to the northward branch of the canyon head refracting more wave energy offshore relative to the old bathymetry. The new bathymetry also tends to reduce waveheights at Black's Beach, as seen in Figure 5 (between x=10000m and x=10500m, and y=5500m and y=6500m). The northward branch of the canyon head reduces wave energy away from its center axis by refraction; once past the canyon head, the energy is refracted toward the coast. The depth contours of the new bathymetry north of the canyon (Figure 3) are less regular than those of the old bathymetry. This would likely cause local refraction effects which carry forward toward the canyon, as seen in the finger-like structures in the offshore area north of the canyon in Figure 5.

6. WAVE MODELING SYSTEM

A nested modeling system has been developed for the NCEX area. The system will be able to simulate wave propagation over the overall NCEX domain, as well as high-resolution nearshore wave transformation and circulation processes in areas of interest.

The SWAN model (Booij et al. 1999; Rogers et al. 2002), mentioned previously, is a phase averaged energy transport model which can nest inside global wave models (WAM, WAVEWATCH) as well as use information from measurements to propagate wave energy over arbitrary-size domains. Wave information from the model can be output anywhere in the domain; in the present application, directional spectra from the model are output along lines corresponding to the offshore boundaries of the nearshore grids.

The nearshore wave model REF/DIF-S (Chawla et al. 1998) is then run for the smaller areas. REF/DIF-S includes wave diffraction, which can be important in nearshore areas. It is also a phase-averaged model, and thus phases must be assigned to the input spectra. The technique used is described in Kaihatu et al. (2002b), however, since the REF/DIF-S model is linear, the difference in phase along the offshore boundary for each frequency and direction is more important than the absolute value of the initial phase, since the difference in phase determines the initial wave angle.

Information from the REF/DIF-S model is then input into SHORECIRC (Van Dongeren and Svendsen 2000), a quasi-3D hydrodynamic model. In contrast to two-dimensional flow models, the quasi-3D formulation allows for the additional mixing imparted on the flow by the depth profile of the horizontal velocity. This removes much of the burden on eddy viscosity specification to provide the proper mixing, and allows values of the eddy viscosity coefficient which fall more in line with measurements. Required input from the wave model includes: waveheights, wave directions, near bottom orbital velocities, short wave volume flux (for the undertow calculations) and wave dissipation. It is noted that, while REF/DIF-S is used for the present study, the SHORECIRC model can interface with any applicable wave model, so long as the requisite input fields are calculable.

7. WAVE MODEL SENSITIVITY ANALYSIS

The spectral discretization used by the forecast models and the buoys are quite different (particularly in direction); it would be interesting to investigate the effect this difference has on wave propagation over the NCEX site. (A similar study was performed by Scalvo and Cavaleri (1999) for the Holderness region in England.) The effect of the directional discretization will be the primary focus here; Kaihatu et al. (2002a) determined that wave processes in the nearshore area of the NCEX domain would exhibit the largest sensitivity to the effect of directional binning. Two nearshore areas of interest, roughly comprising the expected instrumented domain for the NCEX experiment, are outlined in Figure 6. The northern area is in close proximity to Black's Beach, while the southern area is near the head of Scripps Canyon. The model

SWAN is then run over the larger NCEX domain, with directional spectral output along the offshore boundaries of the nearshore grids. The REF/DIF-S model then propagates this information over the nearshore grids, supplying the input information required for SHORECIRC. No wind or tidal information is used, and all nonlinear mechanisms in the models are deactivated.

One limitation of the SHORECIRC model is the specification of the lateral boundary conditions. If fluxes at the lateral boundaries are known, they can be specified. Alternatively, these boundary conditions are assumed to be either periodic or closed, neither of which conveniently fits the local domain. The geometry of the NCEX area requires significant care in the specification of these boundaries; this level of caution is amplified with the SHORECIRC model's quasi-3D formulation, which is quite sensitive to deviations from periodicity. Results of this analysis using the SHORECIRC model will be presented at the conference. However, it is still possible to infer much concerning the nearshore circulation field by studying the changes in the forcing (required inputs to SHORECIRC) in the nearshore area.

As mentioned previously, directional spectra from forecast models in present operational use have a directional discretization of 15°. This indicates that wave energy at the spectral peak in the model can actually be propagating at directions ± 7.5° about the reported direction; this half-bandwidth is an estimate of the unresolved error in the directional binning. Directional measurements from the CDIP buoys in the area, in contrast, have a 5° resolution; consequently, the unresolved error of the spectral peak direction is ± 2.5° about the reported direction. This difference in directional discretization is likely to have a large effect in initializing wave models for propagating swell waves over complex bathymetry.

Narrow banded swell with peak periods of T=14*s*, T=16*s* and T=18*s* are used to represent the reported northerly swell (peak directions q=285°, q=290°,q=295°). In reality, swell approaching from the north (typical of late year wave conditions) can be broader in frequency and direction than the test conditions used here due to the effects of local storms. SWAN runs were made with peak directions ± 2.5° and ± 7.5° about each listed peak direction, representing the uncertainty due to the directional binning of the forecast model and the buoy data, respectively. Waveheights, directional spectra, and other information were saved along the offshore boundaries of the Black's Beach and Scripps Canyon areas. The maximum difference in waveheight resulting from the uncertainty due to the directional binning was calculated at each point along the boundaries of both nearshore grids. Figure 7 shows the result for a reported peak direction of q=290° along the offshore boundary of the canyon head grid, while Figure 8 shows the same for the offshore boundary of the Black's Beach grid. The effects of a coarse directional discretization is evident in the wide spread of nearshore waveheights possible in a 15° direction band near Scripps Canyon (Figure 7), particularly for the case of T_p=14*s*. This is in contrast to the offshore boundary of the Black's Beach grid, which appears to be somewhat less sensitive to the effects of coarse spectral discretization, particularly near the north end of the offshore boundary (high y) where the water is significantly shallower. True to intuition, less variation is seen with the 5° directional discretization for all wave periods for both locations. It is evident that the nearshore waveheights evidence strong sensitivity to initial direction, and that uncertainty in the estimation of the initial peak direction due to coarse spectral discretization can lead to a wide range of possible wave conditions in the nearshore.

The recent surveys of the NCEX area were performed by various platforms (research vessels and jetskis). The jetski data comprise the bulk of the new measurements in areas with depths of 8*m* or less. This data was measured at very high resolution in the cross-shore direction, and a resolution of around 100*m* in the longshore direction. The bathymetry data set used in the SWAN runs above is a decimation of the high-resolution bathymetry; the high-resolution (0.15s) bathymetry set is thus not simply an interpolation of the coarser bathymetry. This high-resolution bathymetry data was used for the outlined nearshore areas, and the wave forcing was provided by the SWAN directional spectra at the offshore boundaries of the grids. The REF/DIF-S model was run over the nearshore areas for the wave conditions used for the SWAN runs over the larger area (both the "reported" swell directions and at directions ± 2.5° and ± 7.5° about these directions). The maximum percentage differences between the waveheights resulting from the reported directions and those at the edges of the directional bins were calculated. Figures 9 and 10 show the maximum percentage differences for T_p=18*s* and a reported offshore direction of 290° for the Scripps canyon head. Figure 9 shows the case for a 5° discretization and Figure 10, a 15° discretization. It is evident that, for the 5° discretization, there appears to be at most a 15% variation in waveheight expected due to uncertainty in the initial direction. In contrast, the 15° discretization can lead up to 45% waveheight variation at the Scripps canyon head. Figures 11 and 12 show the same percentage differences for the Black's Beach grid, using the same peak period and reported offshore direction. The 5° discretization, seen in Figure 11, leads to at most a 4% variation in waveheight due to the offshore angle uncertainty. However, the 15° discretization, shown in Figure 12, can lead to 14% variation in waveheight at Black's Beach.

8. CONCLUSION

The dependence of the nearshore wave climate on bathymetry and offshore conditions is significant; this dependence is exacerbated when the bathymetry is complex, such as the site of the upcoming Nearshore Canyon Experiment (NCEX), near Scripps Institution of Oceanography in southern California. The influences of updated survey information and uncertainty in the direction of the offshore wave on nearshore wave predictions were studied. The new updates of the bathymetry evidenced steeper side slopes and a narrower planform of Scripps Canyon than previously seen in the older National Ocean Survey (NOS) bathymetry. Additionally, a smaller, northward-pointing branch of the canyon appeared in the new survey. Based on SWAN runs of presumed northerly swell over the region, the branch had the effect of refracting energy away from Black's Beach (north of Scripps Canyon) and amplifying waveheights just offshore, relative to the old bathymetry.

Global wave models (WAM, WAVEWATCH-III) can provide directional spectra as offshore forcing for nearshore wave models. These spectra are generally reported in 15° directional bins. Measurements from the Outer Torrey Pines Buoy, deployed by the Coastal Data Information Program (CDIP), are reported as directional spectra with 5° directional bins. Nearshore domains were outlined, loosely defining the head of Scripps Canyon and the Black's Beach area. The variations of waveheights at the offshore boundaries of these grids, representing the effect of estimation uncertainty of the peak direction at the offshore edge of the NCEX domain, were calculated using the SWAN model. This revealed (not surprisingly) that greater variations in the waveheights are possible using a 15° angle band than using a 5° angle band, indicating an increased uncertainty in the nearshore wave climate using forecast wave conditions from models and potentially impacting experiment planning and instrument deployment. This variability was also seen in the waveheight fields in the nearshore domains, which resulted from running the REF/DIF-S model forced by SWAN. There appeared to be somewhat less sensitivity to variation in offshore condition at Black's Beach than the Scripps canyon head area, possibly due to the relatively long slope offshore of Black's Beach.

It is thus apparent that the coarse directional resolution of the operational WAM runs can adversely impact swell predictions in the nearshore (instrumented) areas of the NCEX site. Operational turnaround time requirements, however, dictates this resolution. A potential solution is available via the Navy Swell Model (http://www7320.nrlssc.navy.mil/html/swell/swell.html), which allows accurate propagation of swell generated via global models at high directional resolution.

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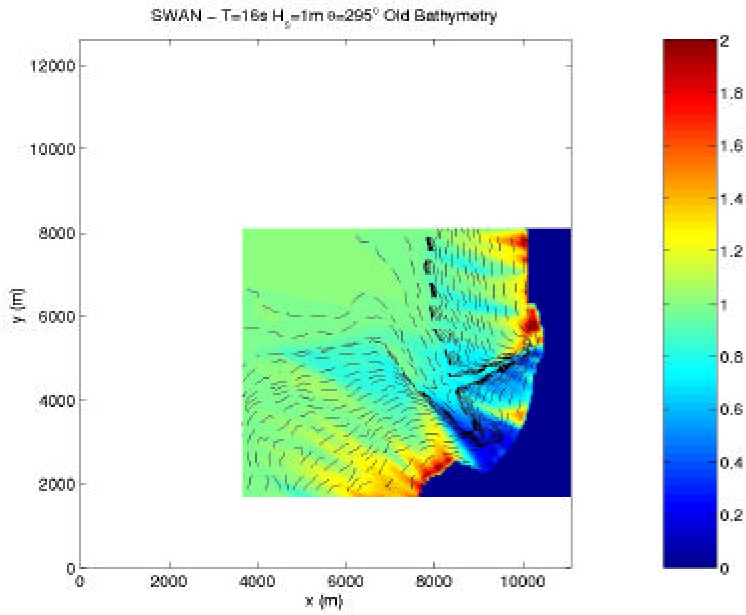

Figure 1. Waveheights from SWAN wave model over NOS bathymetry at NCEX site.

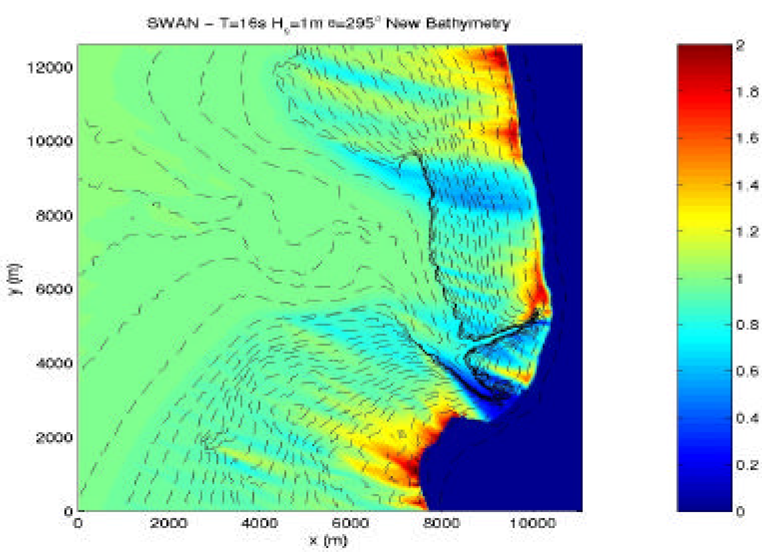

Figure 2. Waveheights from SWAN model over NOS bathymetry combined with recent survey data, NCEX site.

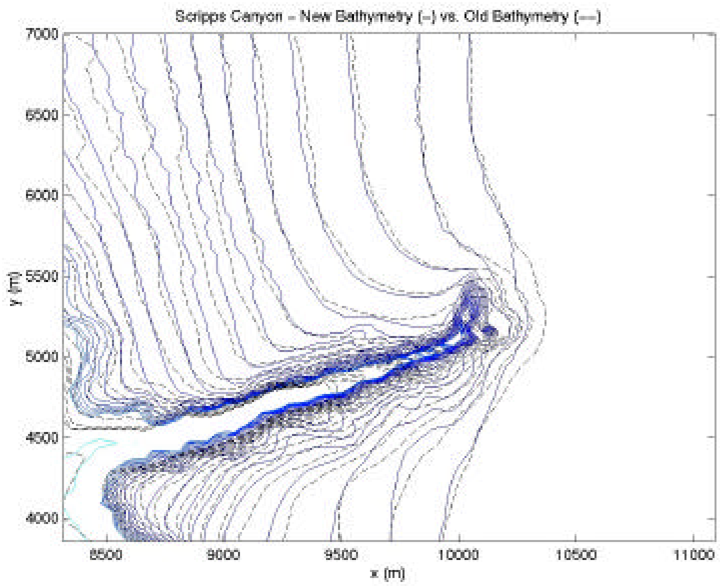

Figure 3. Closeup of bathymetry of Scripps Canyon. Solid lines: new survey bathymetry. Dashed lines: older NOS bathymetry.

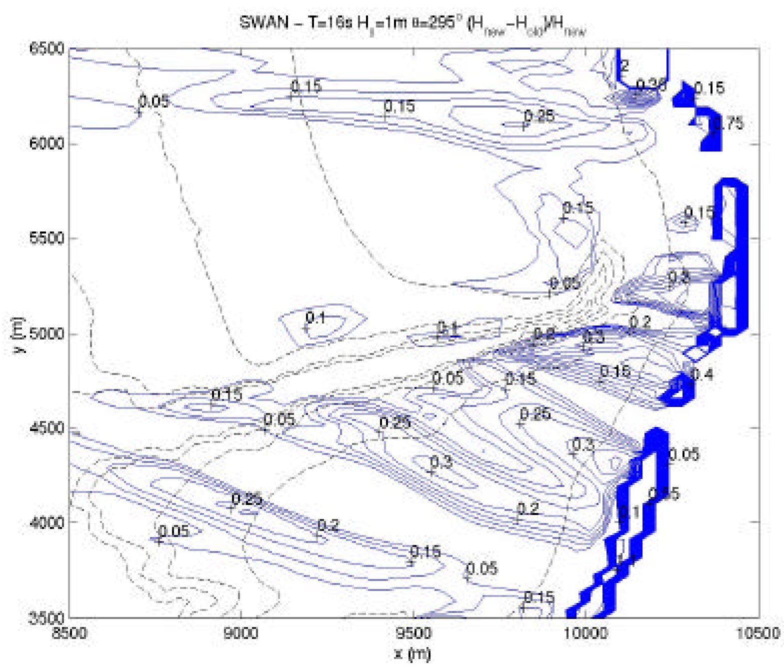

Figure 4. Fraction increase in waveheights for swell condition due to new bathymetry, Scripps Canyon. Contours of new bathymetry shown in dashed lines.

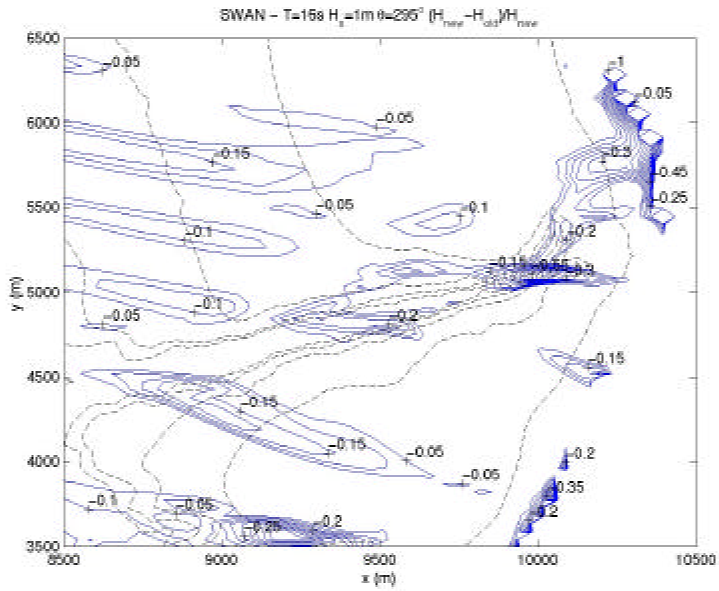

Figure 5. Fraction decrease in waveheights for swell condition due to new bathymetry, Scripps Canyon. Contours of new bathymetry shown in dashed lines.

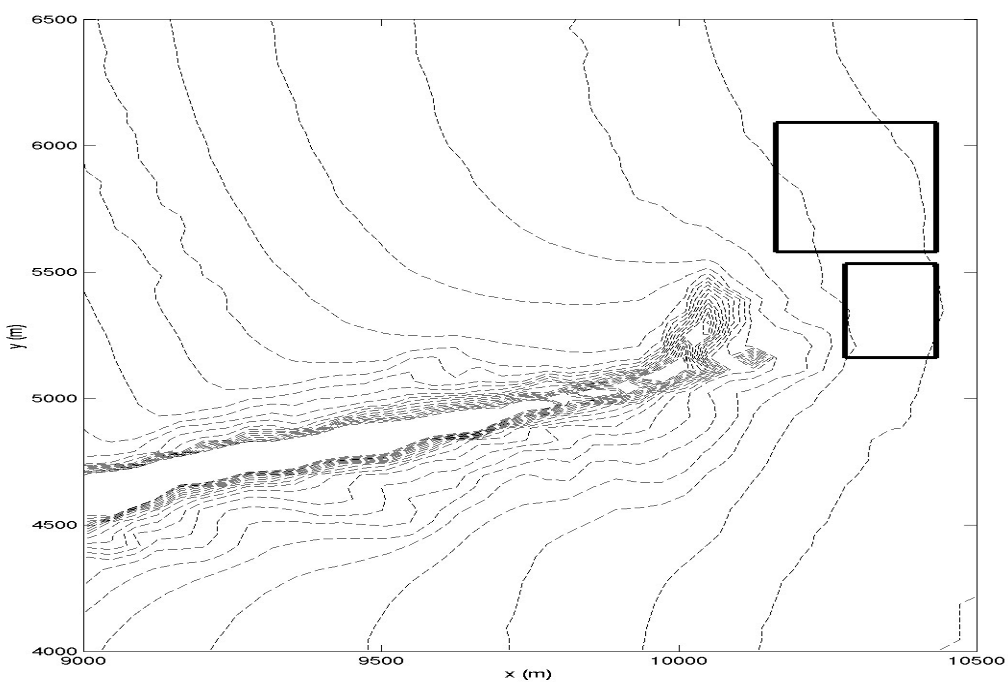

Figure 6. Outlines of nearshore grid areas. Top: Black's Beach grid. Bottom: Scripps canyon head grid. New bathymetry shown in dashed lines.

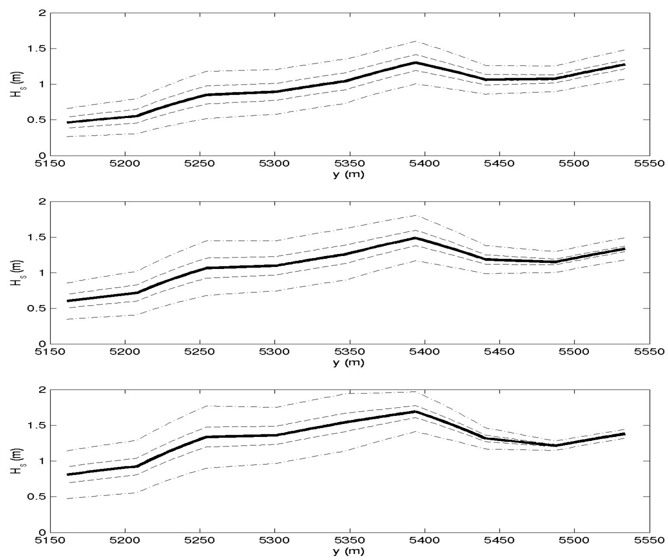

Figure 7. Waveheights along offshore boundary of canyon head grid. Reported peak direction for swell is 290°; waveheights from this reported direction shown in solid lines. Dashed lines show band of possible waveheight variation from 5° discretization. Variations from 15° discretization shown in dashed-dot lines. Top: T_p=18 *s*. Middle: T_p=16 *s*. Bottom: T_p=14 *s*.

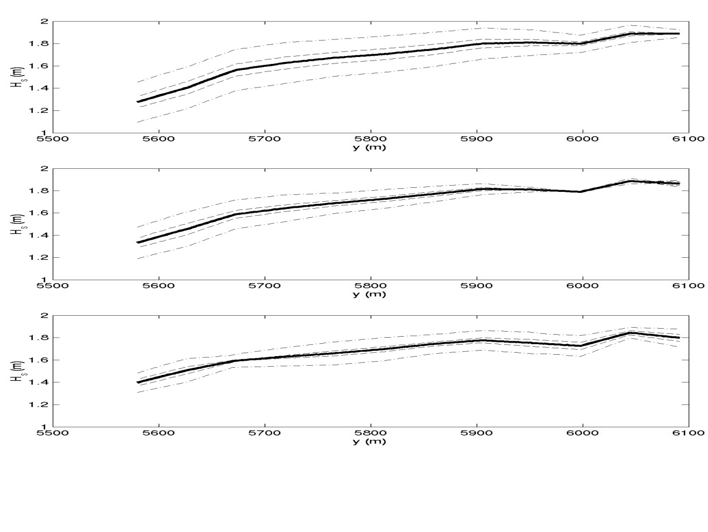

Figure 8. Waveheights along offshore boundary of Black's Beach grid. Reported peak direction for swell is 290°; waveheights from this reported direction shown in solid lines. Dashed lines show band of possible waveheight variation from 5° discretization. Variations from 15° discretization shown in dashed-dot lines. Top: T_p=18 *s*. Middle: T_p=16 *s*. Bottom: T_p=14 *s*.

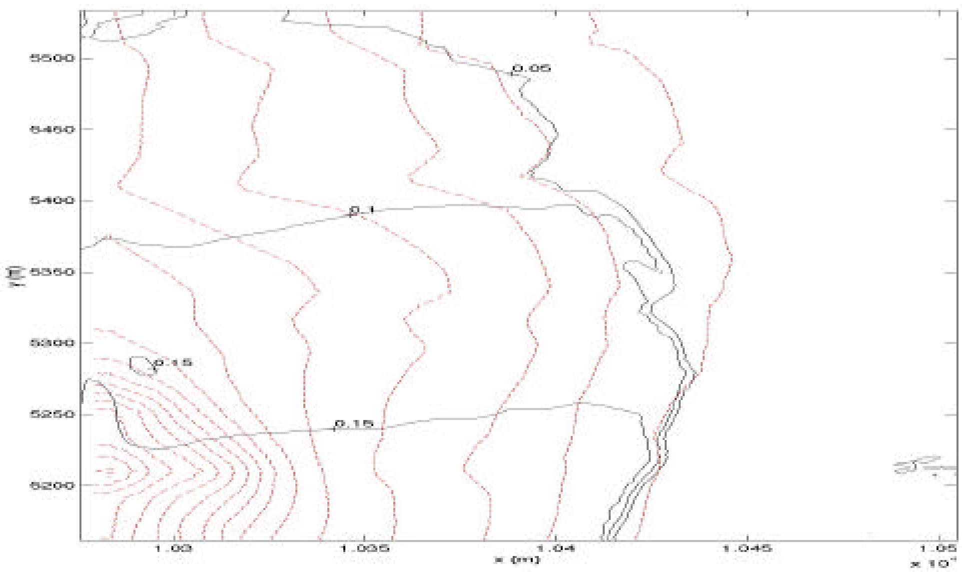

Figure 9. Maximum fraction variation in waveheights within a 5° band about a mean direction of 290° at head of Scripps Canyon. New bathymetry shown in dashed lines. T_p=18 *s.*

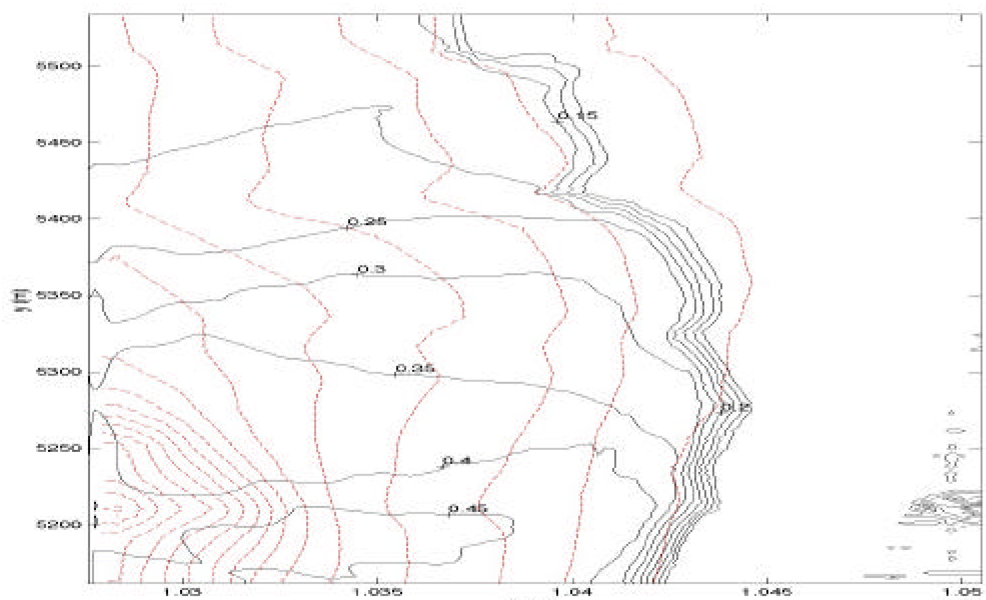

Figure 10. Maximum fraction variation in waveheights within a 15° band about a mean direction of 290° at head of Scripps Canyon. New bathymetry shown in dashed lines. T_p=18 *s.*

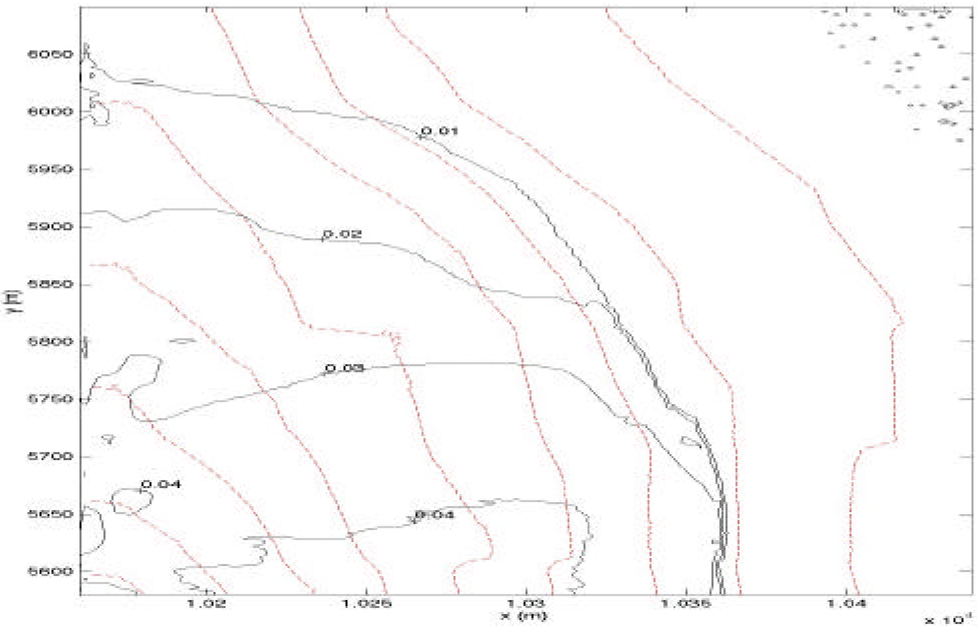

Figure 11. Maximum fraction variation in waveheights within a 5° band about a mean direction of 290° at Black's Beach. New bathymetry shown in dashed lines. T_p=18 *s*.

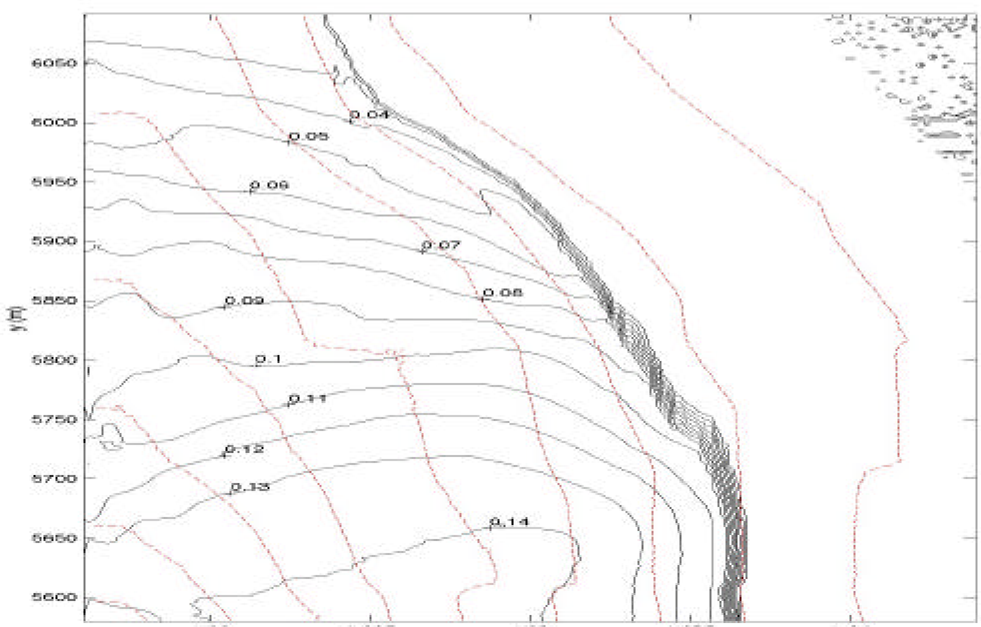

Figure 12. Maximum fraction variation in waveheights within a 15° band about a mean direction of 290° at Black's Beach. New bathymetry shown in dashed lines. T_p=18 *s*.