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Session 1 Presentation - Wave Energy Converter effects on wave, current, and sediment circulation: A coupled wave and hydrodynamic model of Santa Cruz, Monterey Bay, CA

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Wave Energy Converter effects on wave, current, and sediment circulation: A coupled wave and hydrodynamic model of Santa Cruz, Monterey Bay, CA

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Introduction

Characterization of the physical environment and commensurate alteration of that environment due to Wave Energy Conversion (WEC) devices, or arrays of devices must be understood to make informed device-performance predictions, specifications of hydrodynamic loads, and environmental management decisions to physical responses (e.g., changes to circulation patterns, sediment dynamics). Wave energy converter devices will be deployed meters to several kilometers from the shoreline and are exposed to large forces from surface-wave action and currents which will define their performance. Wave-energy devices will be subject to additional corrosion, fouling, and wearing of moving parts caused by suspended sediments in the overlying water. The alteration of the circulation and sediment transport patterns may also alter local ecosystems through changes in benthic habitat, circulation patterns, or other environmental parameters.

The goal of this study is to develop tools to quantitatively characterize the environments where WEC devices may be installed and to assess effects to hydrodynamics and local sediment transport. The primary tools are wave, hydrodynamic, and sediment transport models. In order to ensure confidence in the resulting evaluation of system wide effects, the models are appropriately constrained and validated with measured data where available. Preliminarily, a model is developed and exercised for a location in Santa Cruz, CA for a hypothetical WEC array. An extension of the US EPA's (United States Environmental Protection Agency) EFDC (Environmental Fluid Dynamics Code), SNL-EFDC (Sandia National Laboratories EFDC) provides a suitable platform for modeling the necessary hydrodynamics and it has been modified to directly incorporate output from a Simulating WAves Nearshore (SWAN) wave model of the region. The modeling framework and results will be presented in this document.

Model Development and Application

Circulation and mixing in nearshore regions are controlled by nonlinear combinations of winds, tides, and waves. During a large wave event, wave effects can dominate the nearshore currents and mixing. The modeling approach for investigating WEC devices in the nearshore is structured to capture complex wave-induced currents and mixing, as well as tide- and wind-driven currents. This requires formulation and integration of both a wave model and a transport/circulation model. The final model results are ultimately linked to site-appropriate sediment properties to provide a full sediment transport model for investigating scour and suspended solids. The following sections outline the modeling components and application in Monterey Bay, CA.

Wave Model

The U.S. National Oceanic and Atmospheric Administration's (NOAA) operational wave model, WaveWatch III (NWW3), was used to generate deepwater wave conditions offshore of the site. WaveWatch III is a third-generation wave model developed at the NOAA National Centers for Environmental Prediction (NCEP). It has been extensively tested and validated. For oceanic scales and deep water, NWW3 has proven to be an accurate predictor of wave spectra and characteristics and has therefore become the operational model of choice for NCEP and many other institutions.

As deepwater waves approach the coast, they are transformed by processes including refraction (as they pass over changing bottom contours), diffraction (as they propagate around objects such as headlands), shoaling (as the depth decreases), energy dissipation (due to bottom friction), and ultimately, by breaking. The propagation of deepwater waves into each site was modeled using the open-source program SWAN, developed by Delft Hydraulics Laboratory, which has the capability of modeling all of these processes in shallow coastal waters.

Hydrodynamic Model

The hydrodynamic model used, SNL-EFDC, is based on a US-EPA-approved, state-of-the-art, three-dimensional hydrodynamic model developed at the Virginia Institute of Marine Science by John Hamrick [5], [6], & [7] to simulate hydrodynamics and water quality in rivers, lakes, estuaries, and coastal regions. The SNL-EFDC includes improved hydrodynamics and sediment transport routines [8].

Bottom shear stress, τ_b, is produced at the sediment bed as a result of friction between moving water and a solid bottom boundary. The bottom shear stress is the fundamental force driving sediment transport. Shear stress is denoted as force per unit area (i.e., dynes/cm^2). It has been studied in detail for currents and waves, and can be defined and quantified mathematically given sufficient information about the hydrodynamics of the system. Shear stress is responsible for the initiation of sediment transport (i.e., erosion) and the ability of the flow to keep particles in suspension. The calculation of shear stress in areas such as the Santa Cruz region, where waves play a large role, is outlined in more detail by [2] and [3]. The wave- and current-generated bottom shear stresses are calculated in this effort using the [2] formulation.

The overall modeling approach has limitations that include:

- It is a simplification of a turbulent, chaotic, nearshore process.
- Salinity and temperature gradients are not included at the offshore boundaries. In other words, large-scale ocean circulation is not incorporated into the nearshore region.
- Measurements of currents are only available at nearshore locations for model validation.

Even though the above limitations are considered when assessing the results, this methodology produces accurate estimates of transport due to the dominant nearshore processes in the region (i.e., waves and tides). These can be used to develop quantitative relationships for sediment transport in the vicinity of marine hydrokinetic (MHK) devices and to assess the forces acting directly on the MHK devices.

Santa Cruz Wave Model

The Santa Cruz, CA, coastal region was chosen for the model framework development due to the similarity to the complex environments where MHK devices would be installed. In addition, under the US Department of Defense (DoD) Center for Excellence in Ocean Science (CEROS) research program, existing field data collection and model development efforts were leveraged for this task.

The NOAA operational wave model, NWW3, was used to generate deepwater wave conditions offshore of Monterey Bay, CA. Daily wave parameters, including significant wave height, peak wave period, and wave direction (H_s, T_s and D_p) were obtained for a reference point located at 37.00° N latitude, −122.5° W longitude. A SWAN model was nested with the NWW3 model to predict the propagation of waves into Monterey Bay and nearshore Santa Cruz, CA.

The Monterey Bay SWAN model domain is shown in Fig. 1. Both waves and wind were output at 3 hour time intervals from NWW3. This was the corresponding update duration for the Non-Stationary Monterey Bay SWAN model. NOAA National Data Buoy Center (NDBC) buoys within the domain are noted in Fig. 1. Data from NDBC Buoy 46236 were used to validate the model predictions for wave height, wave period, and mean wave direction. NDBC Buoys 46042 and 46091 were used to validate wind speed and direction. These buoys were selected based on the type of data that each recorded (i.e., Buoy 46236 did not record wind data, but recorded wave height and period). Buoy 46240 was located in shallow water near the southern Monterey Bay coastline, in an area not considered acceptable for deepwater model validation; therefore, its data were not used.

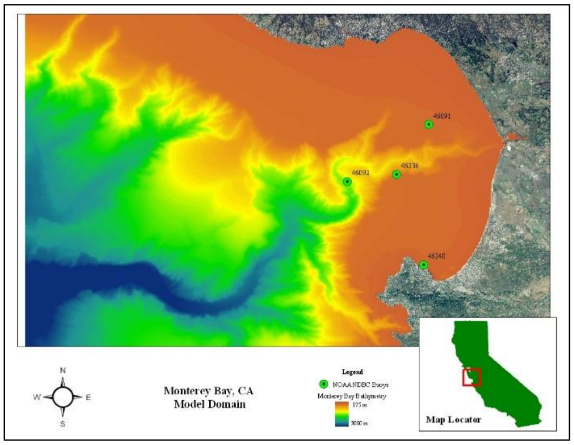

Figure 1. Monterey Bay model domain. NOAA NDBC buoys used for model validation are shown in green.

Wave conditions were outputted for a second nested model domain at a reference point 4 km south of Santa Cruz, CA. The coordinates of the output location were 36.9236° N, −122.0488° W. The grid resolution of the nested computational grid was approximately 0.0003° degrees in latitude and longitude (25 × 30 m^2 in x and y). The wave-spectrum boundary conditions were applied along the offshore (southerly) boundary of the Santa Cruz SWAN model domain. The model was run as a stationary model (no temporally varying wind-field updates). Winds were assumed to have minimal effect on the nearshore wave conditions due to the relatively short distance from the offshore model domain boundary to the coastline. The Santa Cruz SWAN model wave conditions were updated during the period of study (10/18/2009 to 10/25/2009) with the daily Monterey Bay SWAN model output spectra.

A Datawell directional wave buoy (DWR-G) was deployed in the nearshore to measure wave heights, periods, and wave directions during the period of study. The buoy was deployed approximately 100 m south of the Santa Cruz Harbor shoreline and used to validate the nearshore model results. A Teledyne/RD Instruments Acoustic Doppler Current Profiler (ADCP) was deployed in proximity to the wave buoy. The ADCP measured current magnitude and direction in the water column.

Wave Model Validation

Wave heights (in meters), peak wave periods (in seconds), and mean wave direction (in degrees relative to True North) were obtained from the Monterey Bay SWAN model for validation with local NOAA NDBC buoys in Monterey Bay. Data were output every hour at several discrete buoy locations for direct comparison. The ability of a wind-wave model to predict wave characteristics can be evaluated in many ways. Here, model performance (model vs. measured) was assessed through the computation of a scatter index (SI), the root mean squared error (RMSE), and the bias, or mean error (ME). A scatter index [8] is defined as the RMSE normalized by the average observed value. Model performance was computed for both SWAN models: coarse grid Monterey Bay model and the nested, finer grid Santa Cruz model.

Wave heights, peak wave periods, mean wave directions, and total energy dissipation were output each hour from the Santa Cruz SWAN model for every grid point in the domain. The wave heights and wave periods were used to assess model performance with measurements from a locally deployed wave buoy. Output parameters (e.g. wave heights, radiation shear stresses, and dissipation) were used as input data to the nearshore SNL-EFDC model.

Fig. 2 is a comparison of model predictions and buoy measurements. The model performance statistics computed from the Santa Cruz SWAN model comparison to measured data also showed good agreement (see Table 1). The wave heights showed a mean error of +0.04 m (slight over prediction). All model performance values presented here are considered in good agreement. A more detailed description of the data collection effort and model validation conducted for the US Navy is outlined in [1].

Table 1: Model error statistics for the Santa Cruz SWAN model.

Data	RMSe	SI	ME
Hs	0.185	0.218	0.038
Tp	1.197	0.091	0.365
Dir	6.916	0.033	−1.53

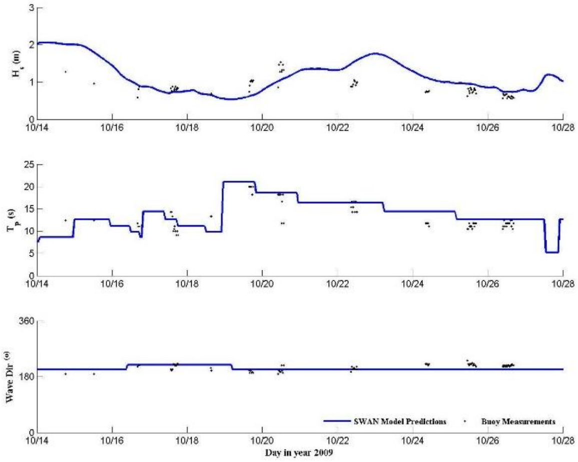

Figure 2. Model (line) representing the wave height (Hs), peak wave period (Tp) and mean wave direction (MWD) obtained from the Nearshore Santa Cruz SWAN model. Measured data (dots) were obtained from the Datawell DWR-G buoy deployed during the field study.

Santa Cruz Hydrodynamic Model

The initial development of the SNL-EFDC model required input of the regional coastal bathymetry. Bathymetry is represented in the numerical model through the creation of a grid and the specification of depth at each cell center. Grid dimensions are selected to balance desired resolution and computational cost. Grid cell size is 20×20 m^2, and the overall grid dimensions are 4.9 km in the alongshore direction (Point Santa Cruz to Soquel Point) and 3 km in the onshore-offshore direction.

The tidal water-level variations corresponding to the conditions in October 2009 were used as model boundary conditions. The water level was applied along the east boundary of the grid. The tidal water level variations were determined from the NOAA CO-OPS (Center for Operational Oceanographic Products & Services) values for tides in the Santa Cruz region (http://co-ops.nos.noaa.gov/index.html). Wind conditions over the model region were assumed to be equivalent to the conditions measured at the Santa Cruz Municipal Wharf, which is central in the model domain. The hourly measured wind speed and direction from the wharf were applied over the entire model domain for the month of October 2009.

Hydrodynamic Model Validation

To ensure that the model accurately simulates currents in the project area, actual currents measured by a nearshore current meter deployed as part of the CEROS studies were compared with those simulated using the wave, tide, and wind boundary conditions outlined. The SWAN model was run for the entire field period to produce time series of wave parameters for the entire model domain. These results were incorporated into the SNL-EFDC model for the time period of interest with the actual tide and winds applied to the domain.

The peak wave heights on 10/14/2009 are shown in Fig 3. Figure 4 shows modeled shear stresses with velocity contours overlaid in the study area. These results demonstrate that along-shore velocities to the east are consistent with drifter observations and ADCP measurements made during the field measurement period. In addition, the combined wave and current shear stresses and velocities will provide the fundamental physical parameters for sediment transport studies under this task.

A quantitative comparison of measured data over the 4 days for which measurements were available to modeled nearshore, depth-averaged current magnitude data for the Santa Cruz nearshore currents model is presented in Fig. 5. Table 2 lists the model performance indicators. On average, the model under predicted the currents by less than 1 cm/s, which is within the 1.5 cm/s velocity error in the ADCP measurements. The combined wave and current model agreement with the measurements is considered excellent.

Table 2. Model error statistics for the Santa Cruz combined wave and current model.

Data	**RMSE**	**SI**	**ME**
Velocity	0.016	0.361	−0.008

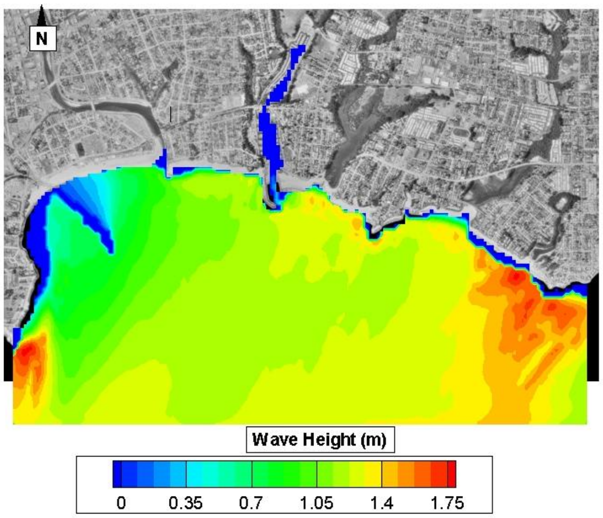

Figure 3. Peak wave heights in the model domain on 10/14/2009.

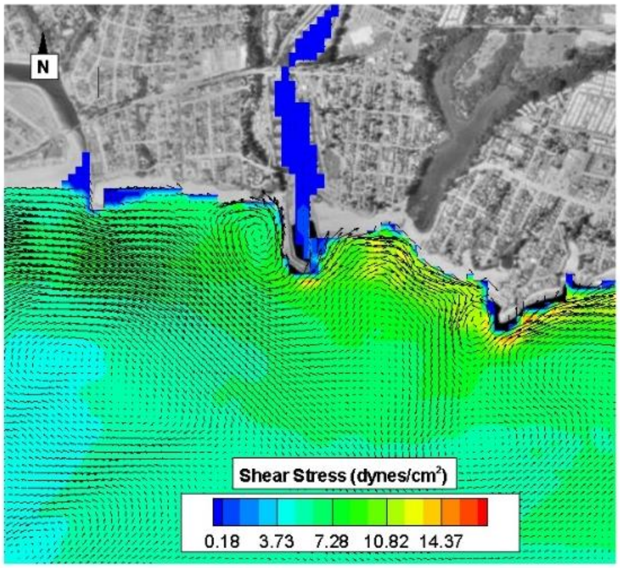

Figure 4. Combined wave and current shear stresses and velocity vectors in the model domain on 10/14/2009.

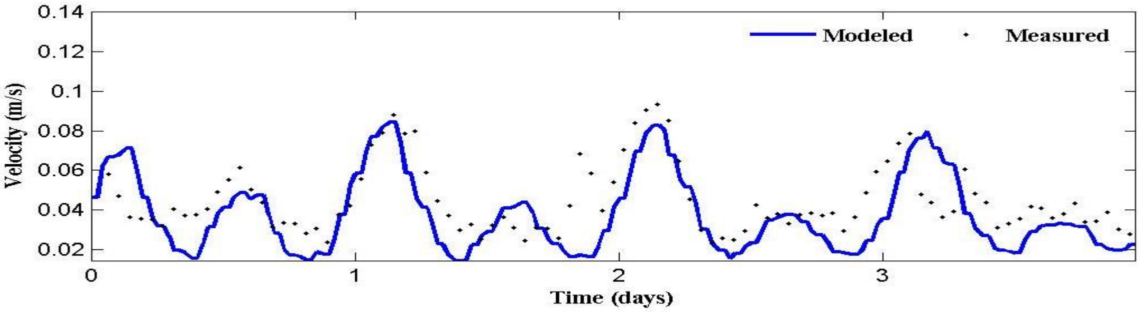

Figure 5. Model (line) representing the current magnitude obtained from the nearshore Santa Cruz SNL-EFDC model. Measured data (dots) were obtained from the RDI/Teledyne ADCP deployed during the field study.

Simulation of WEC Array

In this study, WEC devices are simulated in the SWAN model as discrete obstructions to the propagating wave energy and the subsequent wave fields are passed to the SNL-EFDC model as described above. For the investigation here, the modeled WEC array consisted of 200 individual point absorber style WEC devices organized into a honeycomb shape (Fig. 6). The center of the array was placed at the 40 meter depth contour. The WEC devices were modeled as 10 meter diameter structures spaced approximately 50 meters center-to-center. The distance between device edges was, therefore, approximately 40 meters (or 4 device diameters). The hydrodynamics and sediment transport domain, discussed in the following sections, is focused on the nearshore where the largest potential effects are anticipated. The area of this domain is highlighted in Fig. 6.

An environmentally conservative scenario was assumed for these simulations to evaluate the perceived largest potential effects of a WEC array on the local wave environment. Recent laboratory observations of wave propagation past a WEC array has indicated that “wave absorption is the dominant process inducing the wave shadow” [4]. As such, no wave energy was reflected from the WEC array within SWAN; while 100% of the wave energy was absorbed by the devices. This conservative absorption scenario created a wave shadowing effect in lee of the array. SNL is simultaneously performing related modifications to SWAN to more accurately represent WEC energy absorption that will be incorporated in upcoming work.

For these simulations two wave cases were investigated. A mean wave height of 1.7 m with a period of 12.5 was used as the average condition. Storm conditions were represented by the 95th percentile wave height of 3.5 m with a period of 17 s. The direction of the peak yearly wave energy is from the northwest. These cases are used as generally representative of average and extreme conditions. The modeled wave heights for the 1.7 m average wave case before and after WEC array installation are illustrated in Figure 7 and Fig.8. It is clear that inclusion of devices that inhibit wave propagation cause wave heights to be reduced behind the devices. The change in wave patterns as a result of the obstructions will be incorporated into the hydrodynamic model and subsequent sediment transport model.

Sediment Transport

Wave orbital velocities and wave-driven and tidal currents are among some of the predominant forcing mechanisms in near-shore regions. The combined forcing mechanisms cause shear stresses at the sediment-water interface. When the shear stresses are large enough, individual sediment particles will begin to mobilize, and may travel in bed load (along the seafloor) or become suspended in the water column and be transported with the ambient current. Waves are the primary source of shear stress at the sediment bed in the near-shore region that can cause resuspension of sediment; however, once suspended, sediments will be transported by the combined currents produced by waves and tides. Therefore, calculation of the combined wave-current interactions is necessary to truly represent the expected near-bed forces.

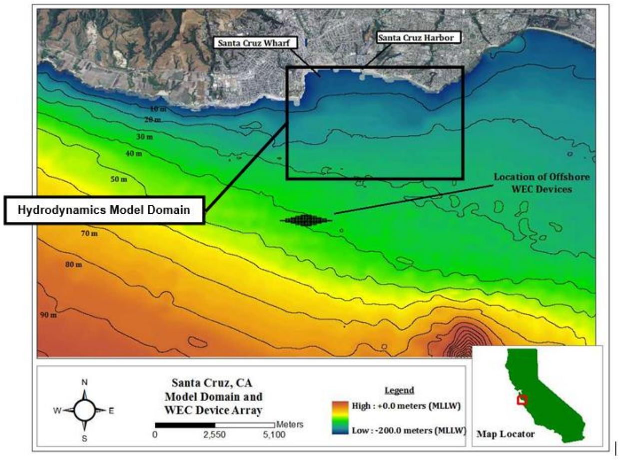

Figure 6. Near-shore Santa Cruz, CA, model bathymetry and WEC device array location.

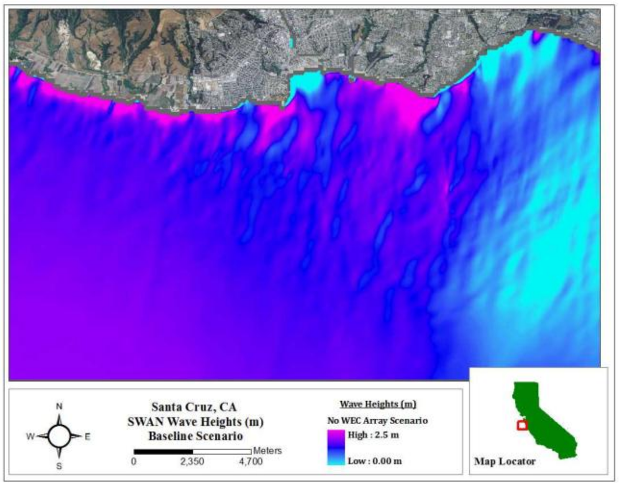

Figure 7. Modeled wave heights prior to the installation of a WEC device array.

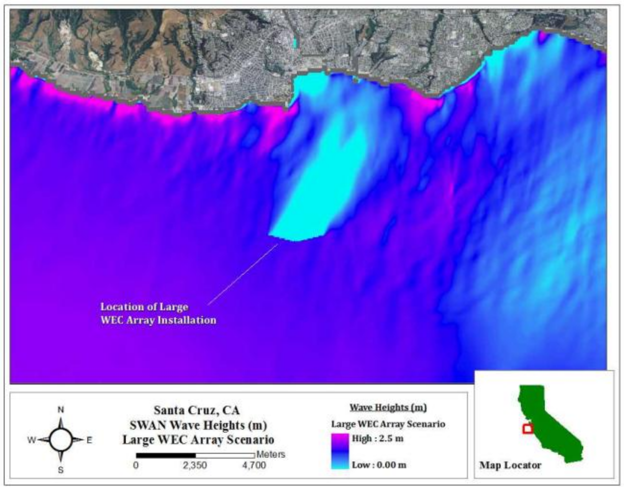

Figure 8. Modeled wave heights after the installation of a WEC device array for an incoming wave height of 1.7m.

The SNL-EFDC model was run for a one week period with the average and extreme SWAN wave characteristics incorporated (e.g. wave radiation stresses and energy dissipation). For the sediment transport simulations the average (1.7 m wave height) and extreme (3.5 m wave height) were used. Near-bottom shear stresses were computed due to the combined wave and currents from SNL-EFDC model following the method of [2], which accounts for the ambient current velocities, wave-induced orbital velocities and seabed roughness. The SNL-EFDC model takes account of multiple sediment size classes, has a unified treatment of suspended load and bedload, and describes bed armoring. Sampling efforts conducted by the USGS and Santa Cruz Port District were used to develop grain size maps of the model region. For these initial investigations a grain size distribution comprised of three separate size classes was developed from the data to define the initial sediment conditions. The size classes consisted of 200, 1000, and 3000 µm sediment representative of fine, medium, and coarse sand and the bed.

As an example of the nearshore changes in the sediment bed, changes after one month are examined. Fig. 9 shows a view of the circulation patterns and resultant bed change both before (baseline scenario) and after installation of the WEC array. Results are shown for the larger 3.5 m wave case.

The baseline results produce behavior consistent with observed nearshore circulation in the Santa Cruz region. The overall circulation and sediment transport are in a "downcoast" or easterly direction. The transport is divided into cells by the numerous rocky points in the region which are erosional (blue) while the beach regions retain sand (red). The blue streaks offshore are also observed in large scale multi-beam surveys of the area as transporting sand waves. The consistency of these results contributes to the overall reliability of the model.

Overall, the WEC array case shows less change in the sediment bed and a disruption of the common easterly currents developed in the nearshore region of Santa Cruz. The circulation in the lee of the array is also altered; reduction of energy in this region creates large offshore flow to balance the higher wave energy up and down the coast during the storm event. The disruption of circulation patterns can alter water quality and seasonal sediment transport patterns that must be investigated on a site specific basis. The implications of these results will be discussed further in the next section, however the comparison of the sediment bed height changes shows that there is a quantifiable effect on circulation patterns and sediment transport in the nearshore due to the presence of the offshore WEC array. It is generally evident that the WEC installation allows for more deposition, however there is a complex interplay that results in "hot spots" of sediment mobility.

Fig. 10 shows the difference in sediment bed height from the model for the 3.5 m storm wave height. The difference plot shows that generally the WEC installation allows for more deposition of any mobilized sediment, yet in the very nearshore to the east of the harbor excess sediment erosion can be seen. This is potentially due to the disruption of sediment supply to these areas during larger events which would normally inhibit erosion. The particle sizes decrease substantially offshore consistent with an overall reduction of wave energy and shear stress in the region allowing finer particles to accumulate at the surface. An unanticipated effect is the reduction of sediment deposition in the harbor mouth which could have a benefit of reducing dredging quantities required after large winter storms.

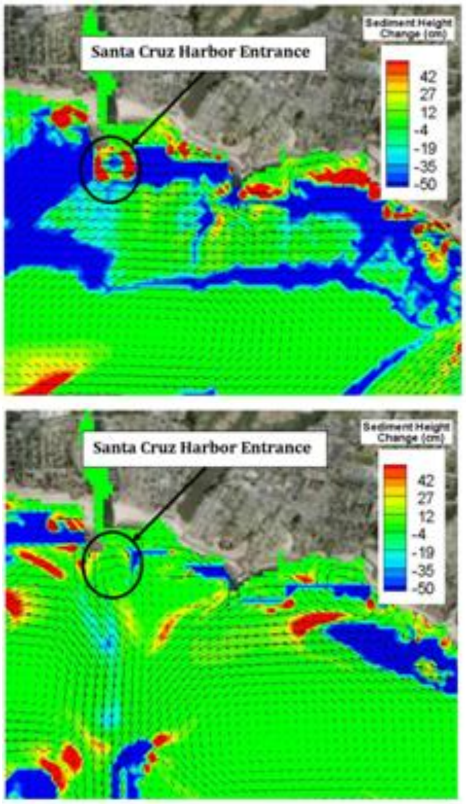

Figure 9. Velocity vectors and resultant sediment bed height change in cm from the combined wave and circulation model for the 3.5 m wave case. The top panel illustrates the baseline case and the lower panel shows the case with the offshore WEC array in place.

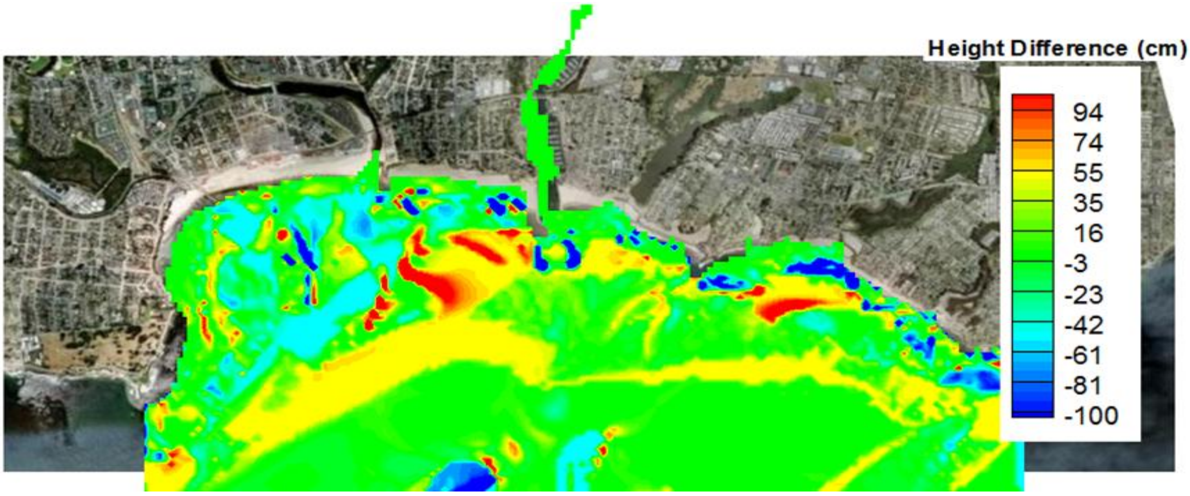

Figure 10. Comparison of change between the baseline model and the WEC array model from the combined wave and circulation model for the 3.5 m waves and normal tides.

Discussion

The goal of this study was to develop tools to quantitatively characterize the environments where WEC devices may be installed and to assess affects to hydrodynamics and local sediment transport. The SWAN wave model coupled with the SNL-EFDC hydrodynamic model developed for the Santa Cruz coast showed that the models accurately reproduced the wave heights and currents in the nearshore region. The large hypothetical WEC array investigated in the modeling study did show alterations to the wave and circulation properties. Differences in surface elevations between the two cases were used as a direct indicator of effects to the nearshore region. The results indicate that there is enhanced sediment trapping in the lee of the WEC array. The behavior is created by a low energy zone in the lee of the array bounded by large waves on either side. In general, the storm wave case waves and the average case waves showed the same qualitative patterns suggesting that these trends would be maintained throughout the year.

The modeling framework of SWAN and SNL-EFDC combined with field validation datasets allows for a robust quantitative description of the nearshore environment within which the MHK devices will be evaluated. This quantitative description can be directly incorporated into environmental impact assessments and eliminate the guesswork as to the effects of the presence of large scale arrays. It is important to emphasize that, in this analysis; all WEC devices are modeled using simple obstruction functions within SWAN that utilize *Transmission* and *Reflection* coefficients. In concurrent research activities, SNL has developed a modified version of SWAN, SNL-SWAN, to more accurately represent frequency dependent WEC power absorption and is presently comparing the model to experimental laboratory data. For the present study, an environmentally conservative approach (100% energy extraction) was used to represent WEC obstruction to wave propagation. This is considered environmentally conservative because physical environmental changes are expected to increase as more energy is removed from the propagating waves by WEC devices. In parallel activities, SNL is beginning to exercise SNL-SWAN within real-world model domains to more accurately characterize the alterations wave propagation and nearshore circulation and sediment transport.

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