Numerical modeling of the effects of wave energy converter characteristics on nearshore wave conditions

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Abstract

Modeled nearshore wave propagation was investigated downstream of simulated wave energy converters (WECs) to evaluate overall near- and far-field effects of WEC arrays. Model sensitivity to WEC characteristics and WEC array deployment scenarios was evaluated using a modified version of an industry standard wave model, Simulating WAVes Nearshore (SWAN), which allows the incorporation of device-specific WEC characteristics to specify obstacle transmission. The sensitivity study illustrated that WEC device type and subsequently its size directly resulted in wave height variations in the lee of the WEC array. Wave heights decreased up to 30% between modeled scenarios with and without WECs for large arrays (100 devices) of relatively sizable devices (26 m in diameter) with peak power generation near to the modeled

incident wave height. Other WEC types resulted in less than 15% differences in modeled wave height with and without WECs, with lesser influence for WECs less than 10 m in diameter. Wave directions and periods were largely insensitive to changes in parameters. However, additional model parameterization and analysis are required to fully explore the model sensitivity of peak wave period and mean wave direction to the varying of the parameters.

Keywords: wave energy converter (WEC); wave modeling; model sensitivity; Simulating WAVes Nearshore (SWAN); nearshore wave propagation

1. Introduction

In order to effectively convert wave energy into commercial-scale onshore electrical power, arrays of multiple wave energy converter (WEC) devices are necessary. The deployment of WEC arrays will likely begin small (pilot-scale or ~10 devices) but could feasibly number in the hundreds of individual devices at commercial-scale. As the industry progresses from pilot- to commercial-scale, an understanding of the effects of WEC arrays leeward of the deployment site and on the nearshore environment will become increasingly important. WEC arrays have the potential to alter nearshore wave propagation and circulation patterns and possibly modify sediment transport patterns (e.g., Gonzalez-Santamaria et al., 2013), which could have detrimental effects on ecological processes and local socioeconomic services. To help accelerate the realization of commercial-scale wave power, it is necessary to evaluate the potential environmental effects of WEC arrays and inform environmental assessments associated with the regulatory process (e.g., Copping et al., 2014; Leeney et al., 2014; Tiron et al., 2015).

At present, due to the lack of deployed WEC farms, direct measurements of the effects of WEC arrays on nearshore wave propagation are not available. Wave model simulations however, can provide the groundwork for completing such environmental assessments by investigating the sensitivity of predictive model results to differing WEC characteristics over anticipated wave conditions. The understanding developed here will allow investigators to conduct predictive environmental assessments with increased confidence and reduced uncertainty in future phases of WEC development.

1.1 Background

Baseline versions of spectral wave models, such as TOMAWAC (TOMAWACE, 2014) and SWAN (Simulating WAVes Nearshore) (Booij et al., 1999; Ris et al., 1999) do not have the inherent capabilities needed for modeling far-field effects of arrays of WECs. These codes effectively model a WEC as an obstacle with a constant, user-specified transmission coefficient (Goda, 1967; d'Angremond et al., 1996) applied across the entire frequency spectrum.

Transmission coefficients determine the amount of wave energy that is absorbed and subsequently allowed to transmit past the obstacles, or WECs.

In a study presented by Millar et al. (2007), potential WEC farm effects on shoreline change were modeled at the Wave Hub site using the native SWAN model and transmission coefficients set at 0%, 40%, 70%, and 90% (corresponding to 100%, 60%, 30%, and 10% wave energy absorption). Millar et al. (2007) concluded that wave heights inshore of WECs decrease linearly

with increasing wave energy transmission. Bento et al. (2014) also simulated WECs as SWAN obstacles with the same transmission coefficients at three different incoming wave directions along the Portuguese coast during two different seasons. They similarly found decreases in significant wave and swell height with increased energy absorption immediately in the lee of the simulated WEC farm.

Several other studies by Rusu and Guedes Soares (e.g., 2008, 2009, and 2013) evaluated WEC and WEC farm effects on the Portuguese coast and neighboring archipelagos. Iglesias and Carballo (2014) determined impact indicators to describe the influence of WEC farm distance to shore on nearshore wave characteristics using constant transmission coefficients determined from laboratory studies. Wave farm configuration sensitivity analysis was performed for the Pelamis WEC by Palha et al. (2010). Chang et al. (2014) evaluated the sensitivity of the native SWAN model to a variety of model parameters with and without a WEC array (transmission coefficient, frequency spreading, directional spreading, and WEC device spacing within the array) and concluded that changes in significant wave height in the lee of a simulated WEC array are most sensitive to wave energy transmission.

While these studies provided insight on wave propagation in the presence of an array of obstacles, they did not take into account WEC device-specific characteristics in the specification of the SWAN model's obstacle transmission coefficients. For example, a later review of the study by Millar et al. (2007) determined that the application of constant obstacle transmission coefficients to model WECs was not well understood and there was not sufficient guidance on how to appropriately account for WEC power performance (ASR Limited, 2007). This directly

motivated the work accomplished by Smith et al. (2012), who modified the SWAN code to account for the frequency- and directionally-dependent power absorption of WECs. With Smith's modifications to SWAN, WEC power performance can be modeled by user-defined frequency- and directionally-dependent power transfer functions. Using this model, the effects of deploying wave farms at the Wave Hub site were re-assessed (Smith et al., 2012).

The development of the SNL-SWAN (Sandia National Laboratories – SWAN) code builds upon the work performed by Smith et al. (2012) by further modifying the native SWAN code to allow for direct importation of WEC power performance data in the form of relative capture width (RCW) curves, or power matrices. RCW curves and power matrices are the current industry standard practice for defining WEC power production (e.g., Hagerman and Bedard, 2003) (RCW curves are analogous to turbine power curves in the wind industry). The incorporation of RCW curves or power matrices removes any uncertainties related to arbitrarily chosen transmission coefficient values. Rather, the transmission coefficients (or WEC power absorption) are calculated directly by SNL-SWAN based on user-defined WEC power performance data. This approach has been verified by comparison to other codes and has undergone preliminary validation by comparison to experimental wave tank data (Ruehl et al., 2013; Porter et al., 2014).

1.3 Objectives

The present study incorporates SNL-SWAN, a modified version of an industry standard wave modeling tool, SWAN to simulate wave propagation through a hypothetical WEC array deployment site on the California coast. The primary objective of the SNL-SWAN sensitivity

study is to investigate the potential effects of a range of WEC devices on leeward and nearshore wave propagation. To accomplish this goal, the following tasks are undertaken:

- Evaluate the modified wave propagation model, SNL-SWAN, which allows the incorporation of device-specific WEC characteristics.
- Perform model sensitivity analysis using SNL-SWAN to examine the effects of WEC characteristics (WEC device type and size, number of WECs, and WEC device spacing within the WEC array) on near-field and far-field wave conditions in the lee of the WEC devices.

2. Methods

2.1 SNL-SWAN

SNL-SWAN was developed to more accurately evaluate WEC farm effects on wave propagation by incorporating a WEC module that accounts for device-specific WEC power performance. Based on the user specified power performance, SNL-SWAN calculates transmission coefficients that are associated with a WEC's power performance. Several methods of determining the transmission coefficient are employed in Version 1.0 of SNL-SWAN. The five methods are employed through switches (specified in the SNL-SWAN input file) in the SNL-SWAN WEC module, where:

Switch 0) SNL-SWAN uses the standard SWAN obstacle treatment (Delft University of Technology, 1993). The transmission coefficient value, K_t , is a constant value entered into the

139 SWAN input file and applied across all wave frequencies. The transmission coefficient
 140 represents the ratio of wave heights incident to and in the lee of the obstacle (or WEC) (Eq. (1)).

$$K_t = \frac{H_{lee}}{H_{incident}} \quad (1)$$

141
 142 Switch 1) SNL-SWAN computes the transmission coefficient from a user-supplied WEC power
 143 matrix (Table 1 shows an example power matrix for a particular WEC). A power ratio is then
 144 calculated at the peak wave period based on the absorbed wave power from the WEC power
 145 matrix (supplied by the user) and the incident wave power (determined from SNL-SWAN). The
 146 transmission coefficient used by SNL-SWAN is calculated based on this power ratio at the peak
 147 wave period, as shown in Eq. (2), and is applied as a constant value across all wave frequencies.

$$K_t^2 = \frac{P_{Lee}}{P_{Incident}} = \frac{P_{Incident} - P_{Absorbed}}{P_{Incident}} = 1 - \frac{P_{Absorbed}}{P_{Incident}} \quad (2)$$

148
 149 Switch 2) SNL-SWAN computes the transmission coefficient from a user-supplied WEC RCW
 150 curve. The transmission coefficient used by SNL-SWAN is calculated based on the RCW value
 151 from the curve given the peak incident wave period, as shown in Eq. (3), and is applied as a
 152 constant value across all wave frequencies.

$$K_t^2 = 1 - \frac{P_{Absorbed}}{P_{Incident}} = 1 - RCW \quad (3)$$

153
 154 Switch 3) SNL-SWAN switch 3 is an extension of switch 1, where distinct transmission
 155 coefficients are applied to each binned wave frequency based on the WEC power matrix. This
 156 results in varying power absorption for different wave frequencies as K_t^2 is a function of wave
 157 frequency.

Switch 4) SNL-SWAN switch 4 is an extension of switch 2, where the RCW curve is sampled independently for each binned wave frequency, resulting in a frequency dependent obstacle transmission coefficient. Please refer to the SNL-SWAN user's manual for more information on the SNL-SWAN WEC module (Ruehl et al., 2014).

Table 1. Power matrix computed for a floating two-body heaving converter (select wave periods and heights shown) (Babarit et al. 2012).

		T_p (s)							
		3	5	7	9	11	13	15	17
H_s (m)	1	2.38	11.41	24.59	43.58	53.08	34.42	19.86	11.78
	2	0	45.28	100.01	153.17	150.81	126.08	60.69	48.03
	3	0	96.17	204.65	357.25	352.72	248.15	136.67	112.52
	4	0	0	366.25	550.98	530.82	419.89	268.44	193.75
	5	0	0	514.29	824.37	617.58	512.41	384.04	257.61
	6	0	0	710.80	973.55	838.26	648.39	501.78	388.41
	7	0	0	781.16	1000	1000	959.05	573.85	449.84

In this paper, all five switches were implemented for a hypothetical WEC array in Monterey Bay, CA. Although it is not an ideal WEC farm location with respect to its wave climatology, the site was chosen based on available wave model validation data as well as previous wave model assessments conducted in the region. The sensitivity analysis was performed for the power

matrices of a variety of existing WEC devices based on the numerical benchmarking paper by Babarit et al. (2012).

2.2 Wave Model Validation: Monterey Bay, CA

SNL-SWAN wave propagation calculations defer to the native SWAN code for cases without obstacles. Therefore, initial site-specific wave model validation was accomplished using the native SWAN model. Deep-water waves were propagated from offshore to shallow water for a study site in Monterey Bay and coastal Santa Cruz, CA. Several local National Oceanic and Atmospheric Administration National Data Buoy Center (NOAA NDBC) buoys provided measurements of wave heights, wave periods, wave directions, wind speeds, and wind directions at Monterey Bay buoy locations dating as far back as 1987. Data from NDBC buoy 46042 (36°47'29"N, 122°27'6"W; 2098 m water depth) were used to derive Monterey Bay domain boundary conditions. Data from NDBC buoy 46236 (36°45'39"N, 121°56'48"W; 145 m water depth) were used to validate the Monterey Bay SWAN model predictions for significant wave height (H_s), peak wave period (T_p), and mean wave direction (MWD). Additionally, a Datawell DWR-G4 wave buoy was deployed in 5 to 6 m water depth near the Santa Cruz Harbor, Santa Cruz, CA (36°57'35"N, 121°59'56"W) for nearshore wave model validation. The model performance statistics computed for the Monterey Bay and Santa Cruz, CA SWAN model studies showed good agreement between modeled to measured data (Table 2). The wave model and validation are further discussed in Chang et al. (2010, unpublished).

Table 2. Native SWAN model error statistics calculated for the Monterey Bay and Santa Cruz, CA wave model validation studies.

Wave Parameter	Monterey Bay			Santa Cruz		
	RMSE	SI	ME	RMSE	SI	ME
H_s	0.29	0.17	-0.06	0.19	0.22	0.04
T_p	2.78	0.26	-0.37	1.20	0.09	0.37
MWD	21.6	0.08	6.34	6.92	0.03	-1.53

RMSE = Root mean square error; SI = scattering index; ME = mean error or bias.

All SWAN and SNL-SWAN model validation, as well as verification, evaluation, and sensitivity analysis runs (see Sections 2.3 and 2.4) employed nautical coordinates in a spherical grid. The computational grids were uniform and rectangular. Monterey Bay high resolution digital bathymetric data were obtained from the NOAA National Geophysical Data Center (NGDC; <https://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html>) and Santa Cruz model domain bottom bathymetry was obtained from high resolution single-beam survey data obtained in November 2009 (Chang et al., 2010, unpublished). The number of directional meshes was specified as 40 equally spaced subdivisions of a 360° circle (every 9°). The frequency resolution was 24 logarithmically spaced frequencies between 0.042 and 1 Hz. SWAN and SNL-SWAN were commanded to utilize the JONSWAP spectrum with default parameters. SWAN was run in first-generation mode with default diffusion and Collins (1972) bottom friction coefficient, wave breaking and triad wave-wave interactions turned on, and diffraction turned off.

2.3 SNL-SWAN Model Verification

SNL-SWAN was evaluated for functionality and comparability to the native SWAN code by using a two-nested model domain in Monterey Bay and Santa Cruz, CA, similar to that presented by Chang et al. (2014) (Figure 1). The coarse-grid (herein referred to as the Monterey Bay model domain) resolution was 0.001° in latitude and longitude. The model was run as a stationary model, i.e. meteorological and hydrodynamic conditions at the offshore boundaries were kept constant. Directional wave energy spectra conditions were exported from the coarse resolution model and used as boundary conditions for the nested, fine resolution model (herein referred to as the Santa Cruz model domain).

The grid resolution of the nested Santa Cruz model domain computational grid was matched to the size of the modeled WEC device type. For SNL-SWAN model verification purposes, the device size and type chosen was a 20-m floating two-body heaving converter (F-2HB; Babarit, 2012). The Santa Cruz model grid size was therefore 0.0002° in latitude and longitude. The wave spectrum boundary conditions were applied along the offshore boundaries of the Santa Cruz SNL-SWAN model domain. The nested grid model was also implemented as a stationary model.

SNL-SWAN was operated using switch 0 and compared to results from the native SWAN model to ensure model integrity. The SNL-SWAN and native SWAN model initial wave conditions were: $H_s = 1.5$ m, $T_p = 12.5$ s, $MWD = 205^\circ$, frequency distribution spread of 3.3, and directional distribution spread of 25. The model runs incorporated an array of 10 WEC devices with 86% transmission ($K_t = 0.86$), zero wave energy reflection allowed, centered on the 40 m depth contour. The WEC device array was arranged in a diamond-shape as a representative configuration (Figure 1). WEC devices were simulated in the model with 6-diameter (center-to-

center) spacing between devices. Devices were equally spaced in all directions. Again, the simulated WEC device type was a floating two-body heaving converter with 20 m diameter. The model results were evaluated at six shoreline locations along the Santa Cruz coast on the 10 m, 20 m, and 30 m depth contours (Figure 1). As expected, SNL-SWAN Switch 0 and native SWAN runs yielded identical results, i.e. SNL-SWAN modifications did not affect the functionality or integrity of SWAN (Figure 2).

2.4 SNL-SWAN Model Evaluation

Following general SNL-SWAN model validation, SNL-SWAN switches 1, 2, 3, and 4 were evaluated for the conditions described in 2.1.2 SNL-SWAN Model Verification except without a user-specified transmission coefficient. Results were evaluated for the 18 output locations shown in Figure 1. Results from all four SNL-SWAN switches were identical to each other at the western and easternmost output locations (location numbers 1 through 6 and 16 through 18; Figure 2). The maximum difference in simulated wave height between SNL-SWAN switch 1 and 3 compared to switch 2 and 4 was 0.4 cm at the location number 7, which is directly in the lee of the WEC array with an incoming MWD of 205°. Differences in modeled wave height were 0.2 cm or less at output location numbers 8 through 12; switches 1 and 3 simulated wave heights were consistently 0.1 to 0.2 cm higher than those modeled using SNL-SWAN switches 2 and 4. These differences are likely due to the data interpolation necessary for computing the RCW curve used in switches 2 and 4.

Results from employing a frequency dependent WEC transmission coefficient are minimal for this particular simulation. Switch 2 and switch 4 results are identical. Only a 0.1 cm difference in

258 wave height is observed at output location number 11 when comparing results from switch 1 and
259 switch 3, with slightly less power absorbed (i.e. higher wave height) when using a frequency
260 dependent transmission coefficient. Although no field validation is available for model runs with
261 simulated WECs, SNL-SWAN switches 3 and 4 are assumed to provide the most accurate
262 mechanistic depiction of wave and WEC interaction(s) (e.g., Smith et al., 2012).

264 **3. SNL-SWAN Sensitivity Analysis**

265
266 Model sensitivity analysis was performed using SNL-SWAN in order to understand model
267 behavior in the vicinity of a variety of different WEC devices and sizes, WEC spacing within an
268 array, and number of WECs in an array. Potential alterations to the nearshore wave climate in
269 proximity to the Santa Cruz, CA shoreline due to WECs were explored by simulating eight
270 different WEC device types with seven different diameters (Table 3) arranged in diamond-
271 shaped arrays of 10, 50, or 100 WEC devices that were equally spaced 4, 6, or 8 diameters apart,
272 center-to-center. Because SNL-SWAN is an energy propagation model and the sensitivity
273 analysis was performed to investigate the extraction of energy from incident wave spectra
274 independent of depth, all WECs were simulated as obstacles extending throughout the water
275 column. All model runs were conducted with the WEC array centered on the 40 m depth contour,
276 as shown in Figure 1. The power matrix for each of the eight devices was computed following
277 Babarit et al. (2012) (Figure 3). See Appendix A for a table of notations.

278
279 A total of 288 SNL-SWAN model runs were conducted (72 for each of SNL-SWAN switch 1, 2,
280 3, and 4). Results were compared to seven model runs conducted with no obstacles. The seven
281 runs with no WECs represented each of the seven different device sizes. The initial wave

conditions were determined from statistical analysis of NDBC buoy 46042 (Monterey Bay, CA) wave climatology records, where median values are: $H_s = 1.7$ m and $T_p = 12.5$ s. Although the median wave direction computed from NDBC buoy 46042 wave records is 299° , representative offshore wave conditions were selected based on its potential to alter nearshore Santa Cruz, CA wave properties. Therefore, the MWD chosen was 205° such that wave shadowing effects by land are reduced. The initial wave conditions were held constant for all model runs. SNL-SWAN model parameters were selected based on SNL-SWAN model evaluation results: frequency spread = 3.3, directional spread = 25, directional resolution = 9° , zero wave energy reflection allowed, and no diffraction.

Table 3. WEC device types and associated diameters (maximum of length and width; from Babarit et al., 2012) simulated for SNL-SWAN model sensitivity analysis.

WEC type	Abbreviation	Diameter (m)
Small bottom-referenced heaving buoy	Bref-HB	5*
Bottom-fixed heave-buoy array [#]	B-HBA	5
Bottom-referenced submerged heave-buoy [#]	Bref-SHB	7
Floating heave-buoy array [%]	F-HBA	8
Floating three-body oscillating flap device	F3 OF	9.5
Floating two-body heaving converter	F-2HB	20
Bottom-fixed oscillating flap	B-OF	26
Floating oscillating water column	F-OWC	50

* The Bref-HB published size is 3 m; however it was specified as 5 m in SNL-SWAN model runs due to limitations on computational grid size.

#B-HBA and Bref-SHB were modeled as obstacles that extended throughout the water column although both are devices without surface expressions.

%F-HBA is a multi-body WEC, composed of any number of heaving buoys connected to a submerged structure. The actual dimension of F-HBA is dependent on the number of heaving buoys within its body. It was therefore modeled as a singular 8-m diameter obstacle.

3.1. Model Set-Up

Two or three SNL-SWAN model grids were nested, depending on WEC diameter, to predict the propagation of deep-water waves from offshore of Monterey Bay to nearshore Santa Cruz, CA.

All model runs made use of a coarse, Monterey Bay grid. Its model resolution was 0.001° in latitude and longitude and it was run as a stationary model. Directional wave energy spectra conditions were exported from the coarse resolution model and used as boundary conditions for the nested, finer resolution model domain.

3.1.1 WECs larger than 15 m

In addition to the coarse Monterey Bay grid, a smaller, nested model domain was employed in SNL-SWAN for WEC devices greater than 15 m in diameter (see Figure 1). The finer, inner nested model domain grid size (here, referred to as the Santa Cruz domain) was set equal to the size of the particular WEC device being modeled. This was to establish each device as equivalent to a model grid cell, which facilitates model performance evaluation and assessment.

3.1.2 WECs smaller than 15 m

WEC devices smaller than 15 m in diameter were modeled with a triple-nested SNL-SWAN model. The reason for this additional nested grid was due to model allocation limitations when attempting to model grid cells less than 15 m in dimension. The two finer resolution grids, additional to the Monterey Bay domain, were the WEC model domain and Santa Cruz model domain (Figure 1). For WECs with diameters less than 15 m, directional wave energy spectra conditions were exported from the Monterey Bay model and used as boundary conditions for the WEC model domain.

The grid resolution of the nested WEC model domain was equal to the modeled WEC device diameter. WEC devices that were 5 m in diameter required a smaller WEC domain due to model computational limitations. WEC devices between 6 m and 10 m required a larger WEC domain such that the entire WEC array of up to 100 devices would be accommodated. The WEC nested grid model was also implemented as a stationary model. The WEC model wave spectrum boundary conditions were applied along the southern offshore boundary of the Santa Cruz model domain. The boundary between the WEC domain and the Santa Cruz domain was extended sufficiently to the west in order to avoid boundary effects (e.g., shadowing) that may have inaccurate model artifacts at the 18 model output locations.

The grid resolution of the innermost Santa Cruz model domain computational grid for SNL-SWAN model runs with WEC smaller than 15 m in diameter was 0.00025° in latitude and longitude. The innermost Santa Cruz domain was also implemented as a stationary model.

3.2 Results and Discussion

SNL-SWAN model sensitivity analysis results were retained for each model run. Results included propagated wave heights, wave periods, wave directions, and near-bottom orbital velocities at all grid points in the model domains. Further, the same wave properties were extracted at each of the 18 distinct model output locations (Figure 1) to facilitate point-to-point comparisons. Note that the primary focus of this study is the alteration of the incident wave spectra downstream of the WEC, at nearshore locations. Any secondary waves potentially generated and/or radiated by a WEC is assumed to be insignificant at the scales considered here. Surface-to-surface evaluations (Figures 4, 5, and 6) compare the modeled scenario results to the baseline scenario results, where the baseline scenario does not include WEC devices. Black shading in Figures 4, 5, and 6 indicates no changes in wave parameter values from the baseline scenario. Color bars are included in each figure to define the amount of change, where change is defined as a percentage change from the baseline scenario, where:

$$\text{Percentage Change} = \frac{(\text{Baseline} - \text{Final Value})}{\text{Baseline}} \times 100 \quad (4a)$$

or, for example,

$$H_s \text{ diff} = \frac{(H_s \text{ Baseline} - H_s \text{ WEC})}{H_s \text{ Baseline}} \times 100 \quad (4b)$$

Therefore, a positive change indicates a decrease in the value of the wave parameter in the presence of a WEC array. Negative changes in MWD indicate clockwise rotation of wave direction and positive changes indicate counter-clockwise rotation.

3.2.1 Significant Wave Height

Results of significant wave height predictions from the sensitivity analysis for 50 Bref-SHB type WECs using switches 1, 2, 3, and 4 are shown in Figure 4. The Bref-SHB WEC is relatively small (Table 3) with relatively low power absorption values (Figure 3). Similar to the SNL-SWAN model evaluation results, switch 2 and switch 4 resulted in greater wave height reduction in the presence of the WEC array as compared to switch 1 and switch 3, again likely due to the effects of the interpolating data when computing the RCW for switches 2 and 4. Further differences in decreased wave height are found when comparing results from employing constant frequency versus frequency-dependent transmission coefficients (i.e. switch 1 and 2 versus switch 3 and 4). For the Bref-SHB WEC, SNL-SWAN model runs with frequency-dependent transmission coefficient (switches 3 and 4) result in up to 0.17% more wave height reduction (output location number 7 comparison between switch 2 and switch 4). Increased wave height reduction (or more power absorbed) for SNL-SWAN switch 3 and 4 runs is also observed for the B-HBA, F3 OF, and F-HBA WEC device types regardless of WEC spacing or the number of WECs in the array (not shown).

However, SNL-SWAN model runs with frequency-dependent transmission coefficient at times resulted in less wave height reduction. This is illustrated in Figure 5 for the B-OF WEC type and also holds true for the F-2HB and F-OWC devices. These three device types are the three largest modeled WECs (Table 3) and have more or less symmetrical power matrices as a function of period as compared to the smaller WECs, which generally exhibit maximum power at the lower wave periods and decreasing power with increasing period (Figure 3). For the simulations

performed here, smaller WECs (less than 10 m diameter) with asymmetric power matrices result in more power absorption when employing frequency-dependent transmission coefficient. On the other hand, model runs for larger (greater than 10 m diameter) WECs with more symmetrical power matrices result in less simulated wave height reduction when modeled with frequency-dependent transmission coefficient.

Switch 1 model results for all eight WEC buoy types are shown in Figure 6. The model sensitivity parameters are 50 WECs with six diameter spacing for each of the WEC device types. General spatial patterns in wave height reduction are similar for the other three switches and other sensitivity parameters and thus are not shown. For all eight device types, the largest wave height decreases were directly in the lee of the WEC arrays at output location numbers 7, 8, 11, and 12. In general, smaller devices had less impact on wave height as compared to larger buoy sizes. Exceptions to this statement were the Bref-SHB buoy (7 m), which exhibited wave height reductions of roughly equal magnitude as the B-HBA WEC type (5 m) and the F-OWC buoy (50 m), which had less of an impact on wave height than the 26 m B-OF device type (Figure 6). The magnitude of wave height reduction was directly correlated to the WEC's power matrix values at the modeled incoming wave height and period, with larger values resulting in more reduction in wave height and *vice versa*.

The largest spatial (horizontal or along-shore) wave reduction effects were observed with the F-OWC device, which makes intuitive sense given that these were the largest of the modeled devices and were thus also spaced furthest apart, i.e. influencing a wider swath of the incident wave field.

408

409 Figure 7 summarizes model sensitivity to the following varied parameters: WEC buoy type,
410 WEC power absorption, number of WEC devices in the array and number of WECs in an array
411 including consideration of the sum total of power absorbed, and WEC spacing and WEC spacing
412 including the influence of the WEC array footprint area (i.e. wave height difference with and
413 without WECs divided by the total area occupied by a WEC array including the spacing in
414 between the WECs). General patterns observed in model sensitivity analysis are similar
415 throughout all four switches; therefore results are shown for a randomly selected switch.
416 Variability in wave height percent differences was largest for buoy type, i.e. the model was most
417 sensitive to WEC device type and WEC size with the exception of the F-OWC buoy. The power
418 matrix associated with each WEC was generally scaled to WEC size, i.e. larger buoys exhibited
419 greater power absorption as compared to smaller devices, with the exception of the F-OWC
420 buoy. WECs with higher power absorption resulted in greater wave height reduction. This is
421 illustrated in Figure 7B, where each WEC device type is represented by its average power
422 absorption as calculated by SNL-SWAN.

423

424 As expected, the larger the number of WECs in the array, the greater the difference between
425 modeled wave height with and without obstacles (Figure 7C). Again, these results are directly
426 correlated to WEC power absorption, i.e. more buoys will absorb more power. Model results are
427 insensitive to the number of WECs in an array when the total power absorption is considered.
428 Figure 7D shows wave height reduction divided by the sum total of SNL-SWAN calculated
429 absorbed power for all WECs in the array.

430

Wave height reduction was relatively insensitive to WEC spacing (Figure 7E). However, when the area of the WEC array footprint is considered, the model results vary with WEC spacing; wave height reductions decrease with increasing WEC spacing (Figure 7F). This indicates that closely spaced arrays have potentially more effects on nearshore wave propagation as compared to arrays of WECs that are spaced farther apart. Furthermore, output locations that are directly in the lee of the WEC array centerline (location numbers 7, 11, and 12) are more sensitive to the spatial extent of the WEC array (Figure 8). The greater the horizontal distance, i.e. west and east of the centerline of the lee of the WEC array, the more insensitive the model results are to WEC array footprint area. Output location number 4 (Figure 8A) shows increased wave height reduction with farther spaced WECs. This location is largely outside of the WEC array influence except for simulations with the F-OWC WEC – the largest of all WECs modeled.

3.2.2 Near-Bottom Orbital Velocities

Near-bottom orbital velocities (e.g. wave-driven currents) are directly proportional to surface wave expression (i.e. significant wave height). Model simulated decreases in wave height due to WEC power extraction cause a decrease in near-bottom orbital velocities, potentially altering the ambient wave-driven currents in a nearshore environment. Consequently, the percentage differences of the near-bottom orbital velocities were essentially equivalent to those computed from the significant wave height model scenarios. Thus, near-bottom orbital velocity results are not shown here.

3.2.3. Peak Wave Periods

The percentage changes in peak wave periods during this study were negligible, as shown in Figure 9. Within the model parameters, the frequency bin resolution was likely too large to register small changes in wave periods (small changes in frequency would not cause a change in frequency bin in model space). Note that for SNL-SWAN switch 3 and switch 4 simulations, there was no observed changes in peak wave energy despite the frequency-dependent power absorption, also indicating that the model frequency bin resolution was larger than any changes in wave period.

3.2.4. Mean Wave Directions

Changes in mean wave directions are illustrated in Figure 10. Directional changes were most sensitive to WEC spacing when the WEC array footprint area was considered. The closer spaced arrays that occupied the smallest footprint resulted in larger directional rotations. However, all percentage differences between the baseline scenario and a simulated WEC array translated to within $\pm 4.5\%$, corresponding to $\pm 9^\circ$ change in MWD. Negative changes indicated clockwise rotation of wave direction. Positive changes indicated counter-clockwise rotation. Rotation, when it occurred in the model, was relatively large because the directional bin spacing was equal to 9° . Any changes less than this are indeterminable by the model as currently parameterized. Zero wave direction change was observed for modeled devices smaller than 8 m. It is thus surmised that direction changes, if any, caused by the WEC devices were less than 9° . Higher resolution changes in MWD could be ascertained with increased model directional resolution. However, due to model allocation limitations in the present model configuration, model grid resolution or model domain size would be compromised.

4. Summary and Conclusions

The presence of WEC arrays have the potential to alter wave propagation patterns significantly and affect coastal circulation patterns, sediment transport patterns, and alter ecosystem processes. To help accelerate deployment of environmentally friendly WEC arrays, predictive modeling tools have been developed to represent WEC induced changes in wave propagation and evaluate the potential for environmental impact. The present study utilized a modified version (SNL-SWAN) of an industry standard wave modeling tool, SWAN, to examine potential WEC array deployment scenarios at a site on the California coast and investigate model sensitivity so that the model can be effectively and confidently used in environmental studies. This analysis built upon a previous sensitivity analysis in which SWAN model parameters were varied to examine their effect on model results (Chang et al., 2014).

In the present study, SNL-SWAN, was evaluated against the native SWAN code and used to investigate the effects of different WEC devices on nearshore wave propagation. SNL-SWAN sensitivity analysis studies were performed to examine the effects of WEC variations (WEC device type and size, number of WEC devices in an array, and the spacing of the WEC devices within the array) on near-field and far-field wave conditions in the lee of the WEC devices.

The results illustrate that, given the present model setup, the wave heights and associated near-bottom orbital velocities showed decreases of up to 30% between baseline and modeled conditions for 100 devices of the B-OF buoy type. The B-OF power matrix values were largest

for an incident wave height of 1.7 m. Other buoy types resulted in less than 15% differences in modeled wave height with and without obstacles, with lesser influence for buoys less than 10 m in diameter. Although the F-OWC device was the largest device modeled, its power matrix values for an incident wave height of 1.7 m were less than that of the B-OF device and hence its wave reduction potential was less. However, the F-OWC effects extended over a larger spatial extent due to its size and spacing, thereby potentially having a greater effects on the local shoreline.

Model output locations located to the west (output locations 1 through 6) showed relatively little to no change in wave heights compared to the baseline scenario. The largest wave height differences were observed downstream of the array near the array centerline (output locations 7 through 12), where the largest wave shadowing effects are predicted. Additional model output locations to the east of the array (output locations 13 through 18) indicated relatively small changes in wave heights for buoys larger than 9 m in diameter. This is intuitive given that the modeled incident wave direction was from the southwest and these waves refracted toward the shoreline in a counter-clockwise manner.

Wave directions and periods did not appear to be sensitive to changes in WEC and WEC array characteristics except when considering WEC array footprint sizes. However, additional analysis is required to fully explore the model sensitivity of peak wave period and mean wave direction to the varying of the WEC parameters.

The SNL-SWAN Version 1.0 source code is publically available (<https://github.com/SNL-WaterPower/SNL-SWAN/tree/master/bin>), has been verified, and has undergone preliminary validation by comparison to experimental wave tank data. However, it is important to utilize ongoing laboratory studies and future field tests to determine the most appropriate implementation of WEC power performance data. Until actual power matrix values become available or further WEC-specific model enhancements are validated, this study shows that environmental assessments of WEC devices should focus on evaluating a range of WEC characteristics in order to determine the limits of the potential environmental effects resulting from the presence of a WEC array. For more information about the ongoing development, validation, and applications of SNL-SWAN, please see Porter et al. (2015) and Ruehl et al. (2015).

In summary, the present study developed a baseline model understanding while investigating the effects of a range of WEC devices. The sensitivity, optimization, and behavior of the model for various WEC devices provided the basis for a solid model understanding giving the confidence necessary for future WEC evaluations.

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Figure Captions

Figure 1. The Monterey Bay domain, WEC domain (bounded by solid lines), and Santa Cruz (bounded on three sides – north, west, and east – by dashed lines) SNL-SWAN model domains for devices between 6 m and 15 m in diameter. The inset shows a close-up view of the WEC and Santa Cruz domain (boundary between the two marked by the solid line) with 18 output locations and simulated WEC array illustrated.

Figure 2. Simulated wave height for model evaluation runs: (A) native SWAN with transmission coefficient equal to 0.86, and SNL-SWAN (B) switch 0 with transmission coefficient equal to 0.86, (C) switch 1, (D) switch 2, (E) switch 3, and (F) switch 4. The text on the left of each panel indicates the simulated wave height at each of the 18 output locations, which are shown as black dots in all panels and numbered in panel (A). The simulated WEC array is illustrated as small black dots on the 40 m depth contour.

Figure 3. Power matrices as a function of significant wave height and peak wave period computed for the eight different WEC device types modeled in SNL-SWAN sensitivity analysis (from Babarit et al., 2012). (A) B-HBA, (B) B-OF, (C) Bref-HB, (D) Bref-SHB, (E) F-2HB, (F) F3 OF, (G) F-HBA, and (H) F-OWC. Color bar scales differ amongst different WEC types.

Figure 4. Significant wave height percentage decrease using SNL-SWAN switch (A) 1, (B) 2, (C) 3, and (D) 4 for model runs specifying 50 Bref-SHB type WECs with 6 m spacing on the 40

m depth contour. Percent decreases at each of the 18 output locations are listed on the left. The device diameters represented in the figure are not to scale.

Figure 5. Significant wave height percentage decrease using SNL-SWAN switch (A) 1, (B) 2, (C) 3, and (D) 4 for model runs specifying 50 B-OF type WECs with 6 m spacing on the 40 m depth contour. Percent decreases at each of the 18 output locations are listed on the left. The device diameters represented in the figure are not to scale.

Figure 6. Significant wave height percentage decrease using SNL-SWAN with a simulated array of 50 WECs spaced 6 m apart on the 40 m depth contour using switch 1 for (A) Bref-HB, (B) B-HBA, (C) Bref-SHB, (D) F-HBA, (E) F3 OF, (F) F-2HB, (G) B-OF, and (H) F-OWC WEC types. Percent differences at each of the 18 output locations are indicated on the left. Device diameters are not to scale.

Figure 7. Wave height reduction as affected by variations in (A) WEC device type (and size), (B) WEC device (and size) represented by each WEC's average power absorption, (C) number of WECs in a WEC array, (D) number of WECs in an array considering the total absorbed power, (E) WEC spacing, and (F) WEC spacing considering the WEC array footprint area. Results are from SNL-SWAN switch 4 simulations.

Figure 8. Wave height reduction as affected by variations in WEC spacing considering the WEC array footprint area for nine different output locations as indicated in each panel. See Figure 2 for a map of output locations. Results are from SNL-SWAN switch 3 simulations.

589

590 Figure 9. Peak wave period reduction as affected by variations in (A) WEC device type (and
591 size), (B) number of WECs in a WEC array, (C) WEC spacing, and (D) WEC spacing with
592 consideration of the WEC array footprint area. Results are from SNL-SWAN switch 3
593 simulations.

594

595 Figure 10. Mean wave direction as affected by variations in (A) WEC device type (and size), (B)
596 number of WECs in a WEC array, (C) WEC spacing, and (D) WEC spacing considering the
597 WEC array footprint area. Negative differences indicate clockwise rotation and positive
598 differences indicate counterclockwise rotation. Results are from SNL-SWAN switch 2
599 simulations.

600 **Appendix A. Nomenclature**

601

602	B-HBA	Bottom-fixed heave-buoy array
603	B-OF	Bottom-fixed oscillating flap
604	Bref-HB	Small bottom-referenced heaving buoy
605	Bref-SHB	Bottom-referenced submerged heave-buoy
606	F-2HB	Floating two-body heaving converter
607	F3 OF	Floating three-body oscillating flap device
608	F-HBA	Floating heave-buoy array
609	F-OWC	Floating oscillating water column
610	H_{incident}	Incident or incoming wave height
611	H_{lee}	Wave height in the lee of a simulated WEC or obstacle
612	H_s	Significant wave height
613	K_t	Transmission coefficient
614	ME	Mean error or bias
615	MWD	Mean wave direction
616	NDBC	National Data Buoy Center
617	NOAA	National Oceanic and Atmospheric Administration
618	P_{absorbed}	Wave power absorbed by a WEC
619	P_{incident}	Incident or incoming wave power
620	P_{lee}	Wave power in the lee of a simulated WEC or obstacle
621	RCW	Relative capture width
622	RMSE	Root mean square error

623	SI	Scatter index
624	SNL	Sandia National Laboratories
625	SWAN	Simulating WAves Nearshore
626	SNL-SWAN	Modified SWAN model
627	T_p	Peak wave period
628	WEC	Wave energy converter

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Figure 1

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