Wave Energy Converter Effects on Nearshore Wave Propagation

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***Abstract*— The present study utilizes SNL-SWAN (Sandia National Laboratories-Simulating Waves Nearshore), a modified version of an industry standard wave model, to simulate wave propagation through a hypothetical WEC array deployment site on the California coast. SNL-SWAN model simulations were performed in hindcast mode for hourly observed wave data in October 2009. Three different wave conditions were examined more closely based on statistical analysis of the observed data: "average", "south swell", and "typhoon". Model results were compared for runs with an array of 50 floating two-body heaving converters against model runs without. During average wave conditions observed in October 2009, the simulated WEC array had little effect on wave height or direction at select output locations chosen for this modeling study. Waves originating from the south (~180°) resulted in >30% reductions in wave height directly in the lee of the WEC array. These reductions in H_s decreased toward the shoreline to percentage changes of ~5%. Extreme typhoon conditions observed in October 2009 resulted in 40% decreases in H_s in the lee of the WEC array and focused wave reductions along the Santa Cruz shoreline of up to 14%.**

Keywords— **Marine renewable energy, wave energy converter, SWAN wave modelling, marine hydrokinetic, wave propagation.**

I. Introduction

Wave energy converter (WEC) arrays have the potential to alter wave propagation, circulation patterns, sediment mobility, and ecosystem processes. Prior to array deployments, direct measurements of the effects of WEC arrays on wave propagation are not available; therefore wave model simulations provide the means to investigate WEC effects on the nearshore physical environment over a range of anticipated wave conditions.

The present study utilized a modified version of an industry standard wave model, SWAN (Simulating WAves Nearshore, [1]), to simulate wave propagation through a hypothetical WEC array deployment site on the California coast. The primary objective of the present study was to investigate the effects of a simulated WEC array on nearshore wave propagation, given actual measured wave conditions. To accomplish this, SNL-SWAN (Sandia National Laboratories – SWAN; [2]) was conducted in hindcast mode using hourly recorded wave parameters in Monterey Bay, California, USA in October 2009 when known variability in wave height, period, and direction was observed. A 20-m diameter floating two-body heaving converter (F-2HB; [3]) was the WEC device evaluated in this study. Results were used to investigate the modelled nearshore wave conditions in the presence and absence of simulated WECs.

II. Methods

A. Initial Wave Conditions

The NOAA NDBC buoy Station 46042, located 27 nautical miles northwest of Monterey, CA in approximately 2100 m water depth, provided hourly time series records of significant wave height (H_s), peak wave period (T_p), and mean wave direction (MWD) over the duration of October 2009. The month of October 2009 was chosen for this study because of its highly varying wave conditions, which included the remnant of a western Pacific typhoon and several south swell events that impacted the Santa Cruz, CA shoreline (Fig. 1).

Wave heights were highly variable over the study period and ranged between less than 1 m to greater than 5.5 m (Table 1). Peak wave periods generally co-varied with mean wave direction; mean wave direction averaged 288° and decreased below 180° at times including during the typhoon. The wave height, period, and direction recorded during the remnant typhoon were conditions that occurred less than 1% of the time (Fig. 2).

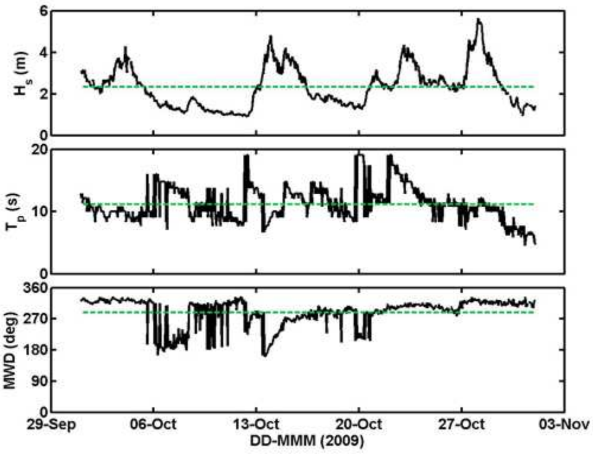

Fig. 1 Hourly H_s, T_p, and MWD measured by NOAA NDBC Station 46042 during the period of October 2009. The dashed green lines indicate mean values.

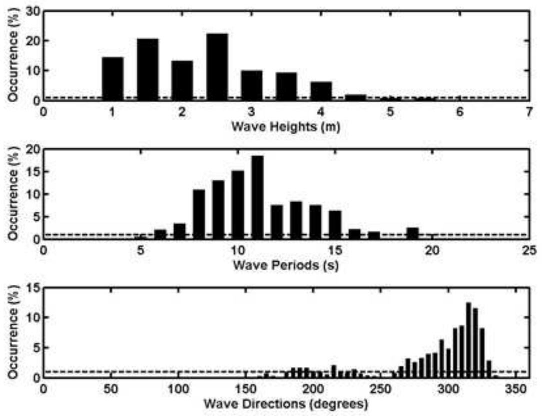

Fig. 2 Frequency of occurrence of NOAA NDBC Station 46042 measured wave height, wave period, and wave direction during the month of October 2009. The 1% occurrence level is indicated by dashed black lines.

TABLE I
STATISTICS FOR WAVE PARAMETER COLLECTED IN OCTOBER 2009 BY NDBC BUOY STATION 46042.

Parameter	Mean	Minimum	Maximum	Standard deviation
H_s (m)	2.34	0.90	5.63	0.99
T_p (s)	11.2	4.55	19.1	2.76
MWD (deg)	288	161	334	41.6

Model results here will be focused on three initial wave conditions based on analysis of October 2009 hourly mean wave directions:

(1) "Average": MWD = 288°, H_s = 1.77 m, and T_p = 12.9 s. These conditions were recorded by NDBC Station 46042 on 17 October 2009 at 19:50.

(2) "South Swell": MWD = 180°, H_s = 1.15 m, and T_p = 12.12 s, occurring on 8 October at 04:50.

(3) "Typhoon": MWD = 161°, H_s = 3.54 m, and T_p = 7.69 s, recorded by NDBC Station 46042 on 13 October at 13:50.

B. SNL-SWAN Wave Model

The modified SWAN model, SNL-SWAN, incorporates device-specific WEC power take-off characteristics to more accurately evaluate a device's effects on wave propagation. SNL-SWAN calculates the effective transmission coefficient of a WEC device by using the incoming wave conditions in combination with a user-specified, device-specific WEC power performance data. A unique transmission coefficient is determined for each frequency bin of the wave spectrum according to the look-up table, resulting in differential absorption of power at each spectral frequency.

SNL-SWAN enables the user to specify one of five different methods of determining the transmission coefficient, defined as switches in the code:

- Switch 0: Defers to the native SWAN obstacle treatment where the transmission coefficient, K_t, is a constant and specified by the user.
- Switch 1: A user-supplied WEC power matrix is used to compute K_t from a power ratio, which is applied as a constant value across all wave frequencies.
- Switch 2: K_t is calculated in SNL-SWAN from a user-supplied WEC relative capture width (RCW) curve and applied as a constant value across all wave frequencies.
- Switch 3: Same as Switch 1 except distinct K_t values are applied to each binned wave frequency based on the WEC power matrix.
- Switch 4: Same as Switch 2 except the RCW curve is evaluated independently at each binned wave frequency.

Therefore, Switches 1 and 2 result in constant K_t across all wave frequencies and Switches 3 and 4 compute frequency-dependent K_t. This study focuses only on SNL-SWAN model results from Switch 1.

C. SNL-SWAN Model Set-Up

The study site was the Santa Cruz shoreline in northern Monterey Bay, California, USA. A two-nested SNL-SWAN model was used to propagate deep-water waves from the northern Pacific Ocean to nearshore Santa Cruz, CA (Fig. 3). The outer, coarse grid model domain, hereafter referred to as the Monterey domain, had a grid resolution of approximately 0.001° in the east-west and north-south directions. The inner, fine-scaled, nested model domain, referred to here as the Santa Cruz domain, employed a grid resolution equal to the diameter of the simulated WEC device, equal to 20 m in latitude and longitude.

SNL-SWAN was run as a stationary model with initial deep-water wave conditions determined from hourly NOAA NDBC Station 46042 wave parameter measurements collected in October 2009. Again, results here are focused on wave conditions recorded on 17 October 2009 at 19:50, 8 October 2009 at 04:50, and 13 October 2009 at 13:50 during average, south swell, and typhoon conditions. The directional wave energy spectra modelled for the Monterey Bay domain were exported and used as the boundary conditions for the Santa Cruz model domain. The model frequency and directional spread were set at 3.3 and 25 and directional resolution was 9° with zero wave energy reflection allowed and no diffraction.

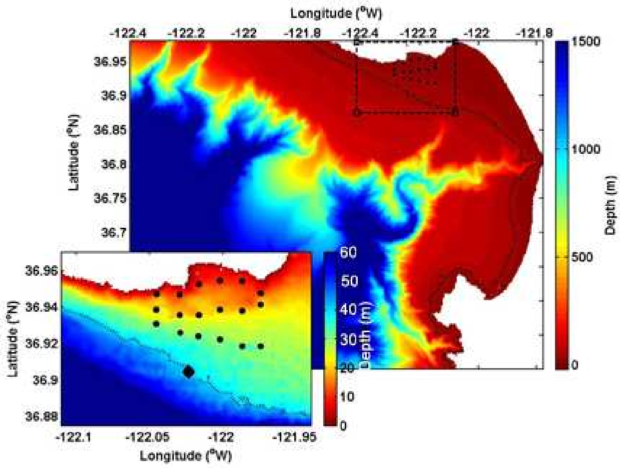

Fig. 3 SNL-SWAN model domains. The Santa Cruz domain is shown in the inset. Model output locations are indicated by large black dots and the simulated WEC array is denoted by a diamond (WEC array is not to scale).

SNL-SWAN Switch 1 was employed for a simulated WEC array comprising 50 F-2HB devices centred on the 40 m depth contour. The modelled WECs were spaced equally in a diamond pattern, 4-diameters (i.e. 80 m) apart, centre-to-centre. The F-2HB power matrix was determined from results presented by Babarit et al. [3] and shown in Fig. 4. The F-

2HB device is optimized for power absorption at wave heights greater than 4 m and wave periods between 8 and 12 s.

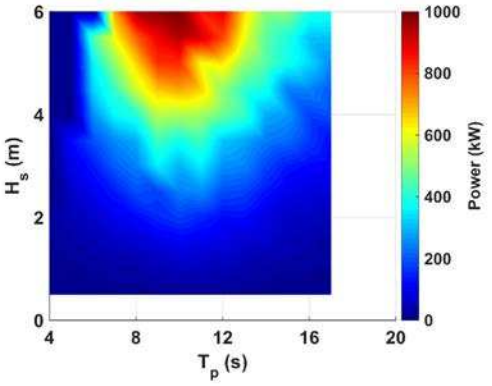

Fig. 4 Floating two-body heaving converter (F-2HB) power matrix (from Babarit et al. [3]).

For comparison purposes, a second set of model simulations was performed without WECs for NDBC Station 46042 measured wave conditions at the dates and times specified above. The effects of the simulated WEC array on nearshore wave propagation were evaluated at all model grid points in the Santa Cruz domain and also at 18 distinct output locations within the Santa Cruz domain. The 18 output locations were located along the 10, 20, and 30 m depth contours along the Santa Cruz shoreline in regions of recreational interest (e.g., popular sight-seeing and surfing locations) (Fig. 3).

III. Results

Model results comparing significant wave height in the presence and absence of WECs are shown as percent differences, where:

$$\text{Percent change} = 100 * [(Hs_{(No\ WEC)} - Hs_{(WEC)}) / Hs_{(No\ WEC)}].$$

Therefore, a positive percent change indicates a reduction in wave height when considering a WEC array and *vice versa*. Changes in mean wave direction are reported as:

$$\text{Difference} = MWD_{(No\ WEC)} - MWD_{(WEC)}.$$

A positive change in mean wave direction indicates counter clockwise rotation of direction and a negative change indicates clockwise rotation. Note that SNL-SWAN model directional bin spacing was equal to 9°; therefore any changes less than this were indeterminable by the model. It is also important to note that changes in peak wave period during this study were also indeterminable by the model due to the model frequency bin resolution.

A. October 2009 Summary

Due to Santa Cruz's south facing coastline, significant wave shadowing by land was observed on the western portion of the study site during periods when mean wave directions were from the northwest (greater than 270°). North-westerly waves were recorded over 75% of the time in October 2009 and resulted in less than 1% reductions in wave height at all 18 output locations (Fig. 5).

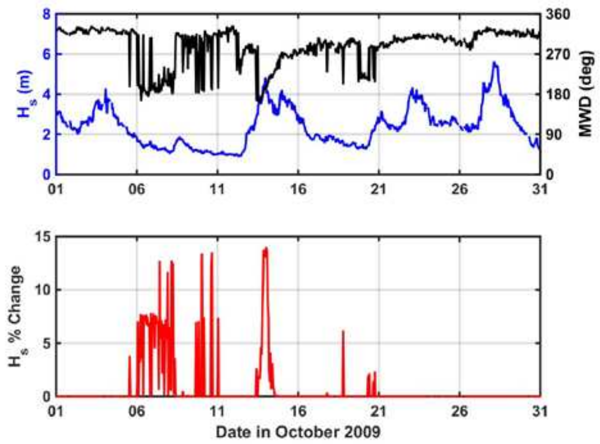

Fig. 5 Top: Hourly significant wave height and mean wave direction as recorded by NOAA NDBC Station 46042. Bottom: Percent change in significant wave height in the presence and absence of WECs for the SNL-SWAN model output location directly in the lee of the WEC array on the 30 m depth contour.

Maximum decreases in wave height were observed during periods of southerly waves (near 180°) when wave shadowing was not an issue. Wave height reductions of nearly 15% were found at output locations on the 30 m depth contour along the angles of incident wave direction (Fig. 5). Model grid locations that were directly in the lee of the WEC array recorded greater than 30% decreases in wave height during periods of southerly waves.

B. Average Initial Wave Conditions

During periods when waves originated from the northwest, negligible (less than 0.2%) changes in significant wave height were observed for all output locations. An exception to this was for the easternmost output points on the 30 m depth contour (numbers 5 and 6; Fig. 6), which are affected by the WEC array for refracted waves originating from the northwest. The percent change in significant wave height between model simulations with and without WECs was less than 1% at these two output locations.

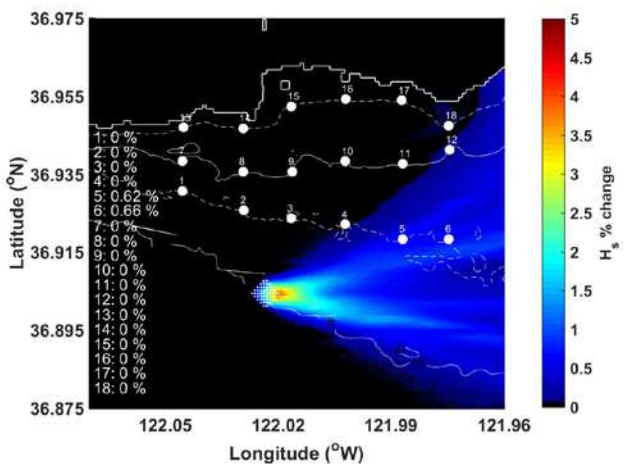

Fig. 6 Percentage change in significant wave height between model runs with WECs and without WECs for average initial wave conditions observed on 17 October 2009. The percent differences at each of the 18 output locations are indicated. The WEC diameters are not to scale.

No rotation in mean wave directions was observed in the presence of a WEC array at any of the output locations during average wave conditions. However, as shown in Fig. 7, ±9° mean wave direction changes resulted from model simulations with WECs near the eastern portion of the Santa Cruz model domain. These indicate negative (clockwise) shifts nearshore and positive (counter-clockwise) changes offshore at the same magnitude as the directional resolution set for the model runs. Any wave direction changes less than this were indeterminable by the model.

A summary of model results during average wave conditions observed in October 2009 is as follows: the difference between significant wave height and mean wave direction for model simulations with and without a WEC array consisting of 50 F-2HB devices spaced 4-diameters apart was negligible at the 18 output locations chosen for this modelling study. However, as shown in Figs. 6 and 7, nearshore locations toward the east of the Santa Cruz model domain would have seen slight decreases in wave height and clockwise changes in wave direction during average wave conditions observed in October 2009.

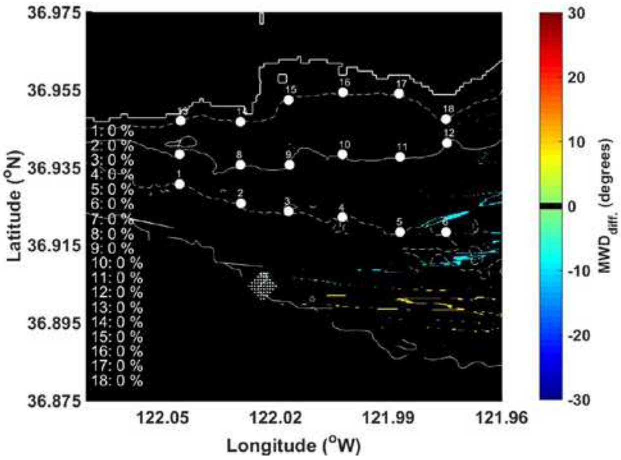

Fig. 7 Change in mean wave direction between model runs with WECs and without WECs for average initial wave conditions observed on 17 October 2009. The differences at each of the 18 output locations are indicated. WEC diameters are not to scale.

C. South Swell Conditions

Mean wave directions of less than 270° were observed 20% of the time and wave directions originating from less than 200° were observed 8% of the time in October 2009. The overall frequency of occurrence of wave directions was comparable to that of the 18 year wave record from the NOAA NDBC Station 46042 between 1992 and the time period of this study in 2009 (Fig. 2).

Significant wave height percent difference and mean wave direction difference results for below average significant wave height (H_s = 1.15 m), above average wave period (T_p = 12.9 s), and mean wave direction directly from the south (MWD = 180°) are shown in Figs. 8 and 9. Wave height decreases of greater than 30% were found immediately downstream of the WEC array. These changes in wave heights decreased toward the shoreline, to values of about 10% at the 30 m and 20 m depth contour and near 5% at the 10 m depth contour. The largest wave height decreases were directly in the lee, to the north of the WEC array (output location numbers 3, 9, and 15; Fig. 8). The along-shore extent of wave height reduction along the 10 m depth contour was limited to output location numbers 14 to the west and number 17 to the east.

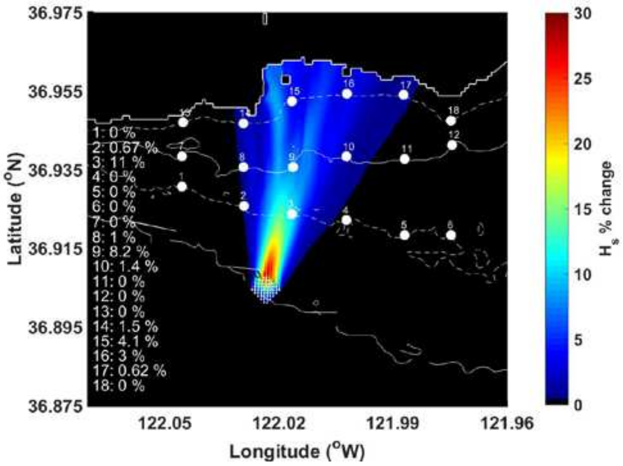

Fig. 8 Percentage change in significant wave height between model runs with WECs and without WECs for south swell wave conditions observed on 8 October 2009. The percent differences at each of the 18 output locations are indicated. The WEC diameters are not to scale.

Mean wave direction changes were again minimal and limited to a few hundred meters along-shore (horizontal) extent. Maximum direction rotations of ±9° (again, equal to the model directional resolution) were directly in the lee of the WECs. Clockwise rotation (negative changes) of wave directions were found slightly to the west of the centerline of the WEC array and counter-clockwise rotation (positive changes) were found slightly to the east (Fig. 9).

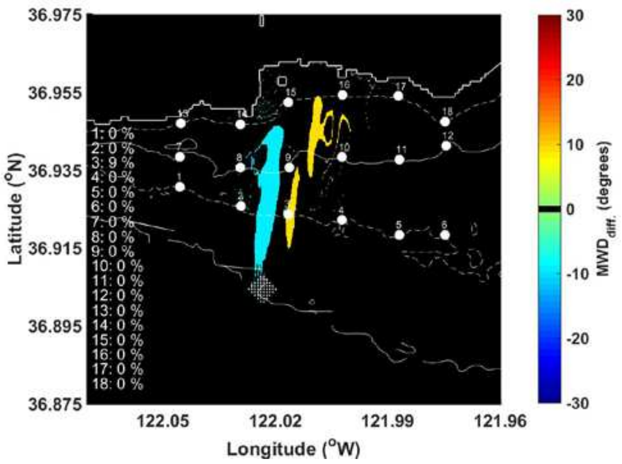

Fig. 9 Change in mean wave direction between model runs with WECs and without WECs for south swell wave conditions observed on 8 October 2009. The differences at each of the 18 output locations are indicated. WEC diameters are not to scale.

D. Typhoon Conditions

The remnant western Pacific typhoon that hit the Monterey Bay, CA region was highly unusual, with wave directions of less than 180° and significant wave heights over 3.5 m. Wave directions of 161° were observed less than 1% of the time over the 18 year NOAA NDBC Station 46042 wave record in Monterey Bay, CA. Wave heights over 3.5 m were more common yet only observed about 10% of the time.

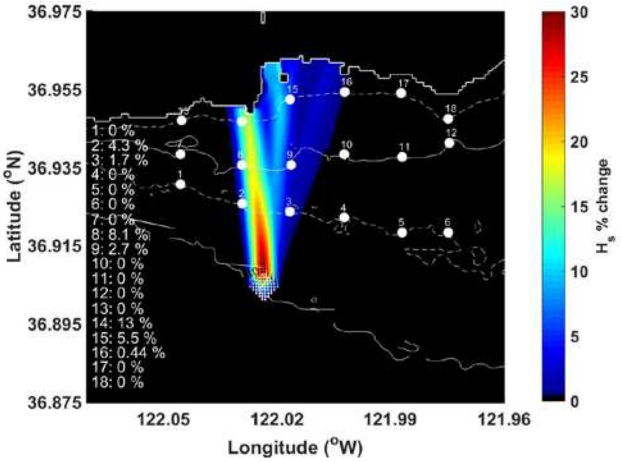

Fig. 10 Percentage change in significant wave height between model runs with WECs and without WECs for typhoon wave conditions observed on 13 October 2009. The percent differences at each of the 18 output locations are indicated. The WEC diameters are not to scale.

The effects of the typhoon on simulated wave conditions in the presence and absence of WECs were similar to those for the south swell case. However, greater wave height reductions were observed because of larger incident wave heights (H_s = 3.54 m). Percent changes in significant wave height were nearly 40% directly in the lee of the WEC array. Interestingly, wave height reductions appeared more focused during the typhoon, with the highest decreases in wave height found downstream of the WECs along the same angle as the incident wave direction at output location number 14 (Fig. 10). Due to the focusing effect, the along-shore extent of wave height reduction was narrower than that observed during south swell conditions. Very little change in mean wave direction was found during the typhoon; no change in wave direction was observed at any of the output locations (Fig. 11).

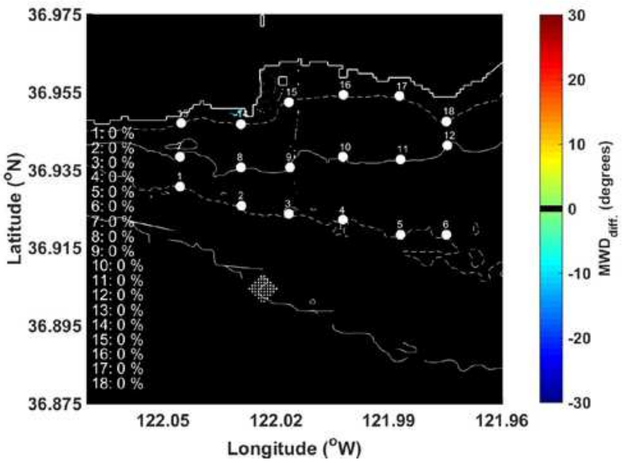

Fig. 11 Change in mean wave direction between model runs with WECs and without WECs for typhoon wave conditions observed on 13 October 2009. The differences at each of the 18 output locations are indicated. WEC diameters are not to scale.

IV. SUMMARY

SNL-SWAN model simulations were performed for hourly NOAA NDBC Station 46042 data obtained for the month of October 2009. Wave model simulations provide the means to investigate WEC effects on the nearshore physical environment over a range of anticipated wave conditions. Three different wave conditions were examined more closely based on statistical analysis of the NDBC data: average, south swell, and typhoon. The model was run with an array of 50 WECs of floating two-body heaving converter device types centred on the 40 m depth contour. Results were compared with model runs without WECs and are summarized here.

- The percentage change in wave height between model runs with WECs and without WECs ranged from 0% to 15% in October 2009 for the 18 output locations in the Santa Cruz model domain.
- Maximum changes in H_s were found for locations downstream of the WEC array, along the angles of incident wave direction.
- Minimal changes in H_s were found for output locations along the western side of the Santa Cruz model domain due to wave shadowing by land.
- Output locations along the 30 m depth contour to the east of the WEC array exhibited >0.5% change in H_s at all times, including for initial wave directions of >270° due to their locations relative to the WEC array and wave refraction.
- Changes in wave period were negligible, primarily due to model constraints.
- Mean wave direction variability due to the presence of WECs was limited to ±9° resolution and was observed at output locations only during southerly wave conditions.
- During average wave conditions observed in October 2009, the simulated WEC array had little effect on wave height or direction at the 18 output locations chosen for this modeling study.
- Waves originating from the south (~180°) resulted in >30% reductions in wave height directly in the lee of the WEC array. These reductions in H_s decreased toward the shoreline to percentage changes of ~5%.
- Extreme typhoon conditions observed in October 2009 resulted in 40% decreases in H_s in the lee of the WEC array and focused wave reductions along the Santa Cruz shoreline of up to 14%.

REFERENCES

[1] N. Booij, C. Ris, and L. H. Holthuijsen, "A third-generation wave model for coastal regions, Part I: Model description and validation," *J. Geophys. Res.*, 104, pp. 7649-7666, 1999.

[2] A. Porter, K. Ruehl, and C. Chartrand, "Further development of SNL-SWAN, a validated wave energy converter array modeling tool," in Proc. 2nd Marine Energy Technology Symposium, 2014, p. 1-9.

[3] Barbarit, A., J. Hals, M.J. Muliawan, A. Kurniawan, T. Moan, and J. Krokstad, "Numerical benchmarking study of a selection of wave energy converters," *Renewable Energy*, 41, pp. 44-63, 2012.