The Effects of Wave Energy Converters on a Monochromatic Wave Climate

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Abstract

To address the rising interest in wave energy converters as a possible means of providing renewable energy, the effects of a wave energy converter in a given wave climate were studied. A dedicated wave energy propagation model was used to simulate the effects of wave energy converters on wave climate in two locations off of the coast of California. Wave amplitude, direction and period were averaged by month based on assimilated buoy data available from the National Oceanic and Atmospheric Administration (NOAA). Wave energy converters were assumed to perform at optimal efficiency as estimated by Previsic and Bedard [2007]. The size and shape of a given wave energy converter was based on the size and shape of three leading wave energy converter designs; The Pelamis Wave Converter, the AquaBUoy and the Wave Dragon. The model showed that the effect that a single wave energy converter had on wave height was less than the naturally occurring monthly standard deviation of wave energy. This was found to be true for the AquaBUoy and Pelamis Wave Converter for all months except those with the smallest mean wave amplitude and standard deviation. The Wave Dragon was found to have wave climate effects larger than the natural monthly standard deviation for most wave climates (assuming a perfect model).

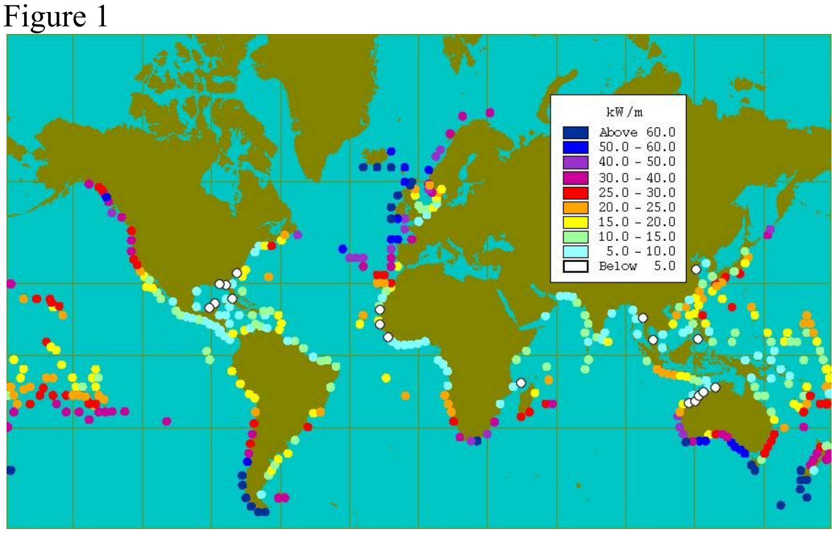
1.0

1.1 Introduction

The interest in renewable energies is currently increasing due to the reported rise in global temperature and the depletion of the earth's fossil fuels [National Geographic 2010]. One area of specific research is that of wave energy. The research is multifaceted and includes research on the efficiency of wave energy converters as well as the availability of energy in the ocean. This study will examine the effects of a wave energy converter on the energy of a monochromatic wave following the dominant direction, mean amplitude and mean wave period of wave energy fields.

There is tremendous energy potential in the ocean. Solar energy has an ideal energy density of 1 kW hr/m^2 [Previsic & Bedard 2007]. Figure 1 shows the distribution of potential wave energy world wide. From Figure 1 it is apparent that the energy potential in the ocean is much higher than that of solar power, with energy densities reaching 60kW hr/m^2. In addition to higher energy density, wave energy has a higher level of predictability.

Figure 1



The world wide wave energy distribution and potential power density according to Previsic & Bedard, [2007].

One state that is beginning to explore wave energy as a means of providing power is California [PG&E WaveConnect, 2010]. Along the west coast of California there is an abundance of incoming power from the ocean waves [Wilson & Beyene 2007; Beyene & Wilson 2007]. According to a report edited by Nelson and Woo [2008] for the California Governor's office, energy usage in California is growing at a rate of 1.25 percent annually. The *Calfornia Global Warming Act of 2006* states that twenty percent of California's electricity must come from renewable energy sources by 2010. However, due to the increases in energy demand the production of renewable energy has not been able to keep up [Nelson & Woo 2008]. Wave energy has the potential to play a significant role in the attainment of this goal. According to the California Energy Commission [2007] the actual potential power available to California is between seven and eight gigawatts which would comprise a quarter of the power demand as of 2006. This does not include potential energy sources in areas that are inaccessible for social, economic or environmental reasons.

In recent years there has been much research done on the potential of converting wave energy into electrical energy. A large portion of the research has gone into engineering different ways of capturing the available energy within the ocean. In their report on WECs Previsic and Bedard [2007] list 46 different companies that are currently developing wave power converters. Each company's designs vary somewhat; however, there are larger groupings that can be made regarding the style with which the energy is obtained.

There are three different general forms of wave energy converter (WEC) that are of interest to this study. They are; point absorbers, attenuators and overtopping devices. Point absorbers are buoys that float on or near the surface of the ocean [Holzman 2007]. With each passing wave the buoy moves in a vertical direction which either creates electricity directly through a magnet and coil apparatus, or powers a piston which pumps a fluid through a turbine. An example of this is the AquaBUoy produced by Finavera. Attenuators work in a similar fashion to point absorbers. A number of buoys floating on their side are connected by pistons. As the segments push and pull on each other with the passing of waves, the pistons connecting them drive a fluid through turbines [Holzman 2007]. An example of this is the Pelamis Wave Converter produced by Pelamis Wave Power. Overtopping devices are the largest of the three types of WECs. They are designed so that wave energy is directed up and into a holding bay, where the water then drains back in to the sea through turbines. The Wave Dragon is an example of an overtopping device [Previsic & Bedard 2007; Holzman 2007]. Wave energy converters are expected to extract 3-15% of the incident wave energy [Previsic & Bedard 2007] depending on the size of the WEC and the ocean conditions. For simplicity, all of the wave energy converters will be modeled as a sink of a fraction of the incoming wave energy in a region similar in size to the desired converter design. Thus, the efficiency and size of the converters will vary by design.

The design and efficiency of the generator continues to be an area with many new developments [Kofoed et al. 2006; Weinstein et al 2004; Jayashankar 2000; Sullivan & Lewis 2008; Duclos et al. 2006; Agamloh et al. 2007; Widden et al. 2008]. While the efficiency of generators continues to be a significant area of research there are already a number of designs that are proving to be efficient through ocean testing and are showing promising results [Previsic 2004]. The Wave Dragon and AquaBUoy have both been tested in open ocean conditions. The Pelamis Wave Converter has also been tested and has begun to show particularly promising results [Previsic 2004].

Extensive research and modeling has been done on the subject of mapping wave energy potential. This modeling relies on the idea of hind-casting, using historic ocean and weather data to model ocean conditions. The Simulating WAves Near-shore (SWAN) modeling program propagates a multiple spectrum wave into a 3D bathymetric model to create an accurate picture of what ocean conditions will be for a give area [Beyene & Wilson 2007]. From that, available energy can be calculated. Wave data is based on historic wave activity gathered from buoy sites. Based on these inputs, SWAN creates a map of wave dispersion, taking into account the effects of refraction, shoaling and diffraction [Beyene & Wilson 2007]. With the testing of enough historic wave data sets an accurate picture of a specific location's wave climate and resulting potential energy can be estimated. This is the process that is used to determine potential sites for wave energy farms. The SWAN model has special application for waves moving into shallow water and the software as well as wave data are publicly available online [Beyene & Wilson 2007].

It is also possible to model deep water wave travel using the program Wave Watch III [Tolman et al. 2002]. Wave Watch III is used to model wind wave production and swell as it travels across oceans. Wave Watch III and SWAN are among those used to establish the available wave energy in various locations for many different wave climates.

While previous research has concentrated on the availability of wave energy [Wilson & Beyene 2007; Beyene & Wilson 2007] and the manner in which it can be extracted [Kofoed et al. 2006; Weinstein et al 2004; Jayashankar 2000; Sullivan & Lewis 2008; Duclos et al. 2006; Agamloh et al. 2007; Widden et al. 2008] there has also been a call for more research into the potential economic, environmental and ecological effects of WEC implementation [Cruz 2008; Nelson & Woo 2008]. In the paper, *Developing Wave Energy in Coastal California: Potential Socio-Economic and Environmental Effects*, prepared for the California Energy Commission and the California Ocean Protection Council, researchers point out a number of different areas that need to be studied with respect to their relationship with wave energy converters and the various positive and negative effects that wave energy converters may have on the environment. They include examining economic and social considerations [Hackett 2008], the potential effects on nearshore and shoreline environments [Nelson & Woo 2008], the potential ecological effects on marine and Anadromous fishes [Nelson 2008], the potential effects of marine birds and mammals [Thompson et al. 2008] and tools for detecting any of the aforementioned effects [Crawford 2008]. A common theme in all of these papers is the need for the assessment of what effects wave energy converters will have on the near shore wave climate. Nelson and Woo [2008] advises creating models to run simulations of waves around WEC array-like objects. They also state that the models should occur prior to implementing significant WEC arrays.

In the report prepared for the California Energy Commission and the California Ocean Protection Council [Nelson & Woo 2008] many different studies are suggested to better understand all of the potential effects of a WEC field. The present study explores the environmental effects of a WEC on a monochromatic wave climate. At this point in time only one study examining the potential effects of WECs on wave fields exists. In his preliminary study on the near shore effects of wave energy converters Don Kingery [2009] addresses the negative effects that a series of wave energy converters may have on the environment based on a two dimensional wave model called CMS-Wave. The report focuses on the potential effects on the shoreline due to modifications of wave driven sediment transport and shoreline wave use [Kingery 2009]. For Kingery's model a base wave spectrum was established and run through the model to establish base levels of significant wave height, period and energy. This was done along all bands of the wave spectrum and wave directions [Kingery 2009]. The model was then run with a given wave energy converter location and size designated as "land" within the model.

The land absorbed, reflected or refracted all wave energy across all fields while allowing energy to pass by on either side. Kingery's [2009] results were then combined with the results where no land masses were in place. The combination of the two separate results gives an estimate of the effects of a wave energy converter. Kingery's [2009] study showed a wave height reduction between one and two inches. The largest decrease in significant wave height was for a wave with a dominant magnitude of 12.5 feet, where a proposed wave energy converter would be at its maximum power generation. The smallest reduction in wave height was found to be at a dominant wave magnitude of five feet. This was attributed to the fact that the energy removed by a wave energy converter declines as the wave energy decreases [Kingery 2009]. The present study will differ from that of Kingery [2009] because it will allow for a decrease in available energy without the effects on wave direction that a land mass would have.

1.2 Background

The modeling technique used in this study is based on Ray Theory and the conservation of energy of a wave moving through a slowly varying homogenous medium. Water waves move in what is known as a wave train or wave packet. In a given wave train in deep or intermediate depth water, waves of different wave lengths will travel at varying speeds; this spreading is known as dispersion. However, within a given wave group the wave energy is conserved and propagates with the group velocity of the waves [Park 2000]. As wave energy is conserved, it is possible to draw a series of rays perpendicular to these wave fronts as they travel; along any given ray, energy will be conserved. A ray is a linear representation of the path of a wave as it travels through a medium, everywhere tangent to the local group velocity. As the wave changes depths, its wavelength and group velocity direction may change, and the path of the ray indicates these changes. Ray theory may be applied as a linear representation of an ocean wave so long as the medium is slowly varying, which is defined such that the change in depth occurs over lengthscales longer than the wave length being considered [Fox-Kemper 2009]. At any point the ray can be examined and it will act as an approximation for the wave propagation as a whole. This theory applies to any wave type (light, ocean etc) traveling through homogeneous material [Fox-Kemper 2009].

Ray Theory is applied through ray tracing. Ray tracing allows us to follow a single "line" or group of "lines" to represent a planer wave front. The rays travel perpendicular to the wave front. At a given time step or location a local derivative can be taken. This gives the ray a new direction and the process is repeated [Chapman & Malanotte-Rizzoli 1989].

Ray Theory, when referring to deep water waves, can be approximated by the superposition of a number of waves of a given period, or monochromatic waves [Cruz 2008]. The basic descriptive components of a monochromatic wave are period (*T*), amplitude (α) and phase velocity or phase speed (*U*). Wave period is defined as the time it takes for a wave to pass a given point [Trujillo & Thurman 2005]. Amplitude is defined as the vertical distance between the peak and trough of a wave [Trujillo & Thurman 2005]. Phase speed is the speed at which a particular phase (crest or trough) on a wave travels horizontally[Trujillo & Thurman 2005]. Frequency is calculated using the equation $\lambda = \frac{1}{P}$. The wavenumber, *K*, is calculated based on $\left|\vec{K}\right| = \frac{2\pi}{T\sqrt{gD}}$ where *T* is mean period, g is gravity and D is water depth. Wave vector components are calculated as $k = \left|\vec{K}\right|\sin(\alpha + \beta)$ and $\ell = \left|\vec{K}\right|\cos(\alpha + \beta)$. Wave energy is given by the formula $\frac{c}{16}H^2T$ in kW/m where $c = \frac{\rho g^2}{4\pi} \cong 7.87\frac{kW}{m}$, *H* is the significant wave height and *T* is the significant wave period [Cruz 2008]. Wave energy flux, which is the power per unit width, is E multiplied by the group velocity $\frac{U}{2}$. For the purposes of this study, only one wave will be examined at a time which means each of these variables will have a unique value at every point in space and time.

As wave energy moves towards shore its energy is dissipated due to the effects of shoaling and the breaking of the wave on shore [Trujillo & Thurman 2005]. Shoaling is the process of a wave moving from off shore to near-shore. As the wave approaches shore, its phase and group velocity decrease, so the incoming energy becomes concentrated in a smaller and smaller region. When the water depth becomes one half the wavelength, the wave will begin to grow in amplitude until the wave reaches shore and the energy dissipates completely in the form of a breaking wave [Trujillo & Thurman 2005]. This energy plays a significant role in numerous environmental and economic processes; including sediment transport, tide pool ecology as well as various fishing and recreational economies [Trujillo & Thurman 2005; Park 2000]. Wave breaking is a nonlinear process and therefore can not be represented directly in a linear theory such as ray theory.

2.0 MODEL DESIGN AND EFFICIENCY

2.1 Purpose of Study

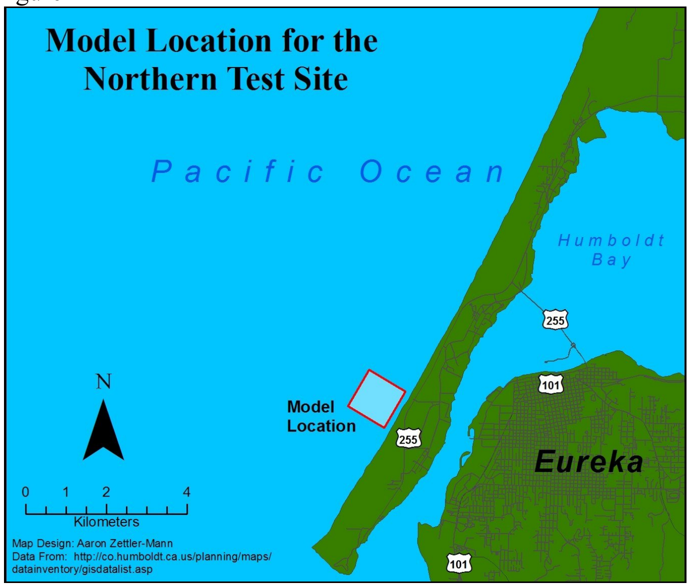
The purpose of this study is to examine the effects of a single WEC which can serve as an estimate of the environmental impacts of a single WEC which can then serve as an estimate of the environmental impacts of a pilot WEC farm or array. By examining the effects of a single WEC we will be better able to assess the positive and negative effects of wave energy converters on ecological, environmental and economic processes. This model differs from Kingery [2009] as it will allow for a decrease in wave energy as a percentage of energy incoming to a particular location as outlined by Previsic and Bedard [2007], as opposed to a ratio of all available energy lost, reflected or refracted to no energy lost. A percentage decrease in energy at a point will better mimic the nature of a wave energy converter because it will not show the effects of processes such as shoaling and refraction on the wave field that an island would.

2.2 Study Locations

Two locations in California were chosen for this study, both of which are north of Point Conception. In addition to both being in the higher wave energy density zones of California, they are both sites actively being examined for the implementation of WEC pilot sites by Pacific Gas and Electric (PG&E) and other private groups. The goal of PG&E's WaveConnect pilot project [PG&E WaveConnect 2010] is to create the infrastructure necessary to allow various wave energy converter manufacturers to install and test their WEC's in a common location in the interest of further developing technology [PG&E WaveConnect 2010].

The first location is off the coast of Eureka, California in Humboldt County. It is roughly located at 40.52N, 124.16W. The Eureka location has a high energy potential in addition to a strong community backing for green energy, including wave energy. The population density at this site is not as large as the southern location and therefore, the potential energy market is smaller. The smaller energy market should not affect the significance of the results of a test WEC farm. The location of the model is shown in Figure 2.

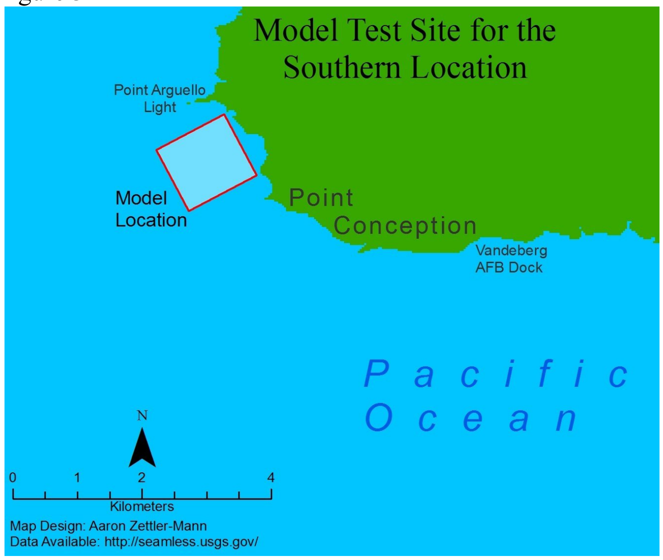
Figure 2



The location of the northern model in relation to Eureka, California. Data from: http://co.humboldt.ca.us/planning/maps/datainventory/gisdatalist.asp [2010]. Map created by Aaron Zettler-Mann [2010].

The second location is off of San Clemente, California and located at roughly 34^0 25' N and 120^0 31' W, shown in Figure 3. The potential energy at this site is not as large as in the northern site, however, it is still north of Point Conception and therefore not affected by the energy decrease caused by the point. It also has the added benefit of being close to a larger population center than the northern site. Additionally, an off shore oil rig is set to be decommissioned in the near future at the southern site. Instead of being decommissioned and removed it can be converted into a WEC power test center. This location would then have the advantage of having a platform where research of all types regarding WECs could be conducted. The power cable leading from the platform to shore is still intact eliminating one of the major costs in the implementation of a wave energy converter project [Wilson 2009].

Figure 3



The location of the southern model off of the coast of Point Conception, California. Data from http://seamless.usgs.gov/ [2010].

2.3 Methods

By running a model based on monochromatic ray equations from Chapman and Malanotte-Rizzoli [1989] for a wave traveling through a slowly varying homogeneous medium this study will show that a single wave energy converter will not have a significant effect on wave climate when compared to the magnitude of normal seasonal and weather related variations in wave energy [Malanotte-Rizzoli 1989]. Inputs will be based on monthly averages for wave period, direction and amplitude. Wave energy converters will be based on the dimensions provided by the manufacturer and the maximum expected efficiency of 15% as predicted by Previsic and Bedard [2007] [PIER 2007]. For this test a WEC has been modeled from each of the three categories. Each WEC was chosen because it has already undergone some open ocean testing. In some cases, the WEC is currently being tested in open ocean conditions, although no test results are currently available. The wave energy converters I have chosen are the AquaBUoy which is a point absorber produced by Finavera, the Pelamis Wave Converter, an attenuator produced by Pelamis Wave Power and the Wave Dragon, an overtopping device created by Wave Dragon. The relative size of the modeled WECs can be seen in Table 1.

Table 1

Wave Energy Converter	Dimensions
Pelamis Wave Converter	3.5m x 120m
AquaBUoy	5 m diameter
Wave Dragon	260m x 150m

Relative sizes of the three wave energy converters simulated.

The data used for wave simulations was gathered from the National Oceanic and Atmospheric Administration. The buoy data gathered was from buoy 46022 for the northern site and from buoy 46051 for the southern site. These buoys were chosen due to the quantity of data available and their proximity to the test locations. Mean wave height (MWH) and period (MWP) were calculated from buoy data gathered every hour that buoys were performing optimally for the years of 1982-2001. Dominant wave direction (MWD) was aggregated from daily data for the years 2007-2008 for buoy 46022 and 1992-1996 for buoy number 46051 as publically available on line from www.noaa.gov on November 17, 2009. Once the raw data was obtained it was consolidated into monthly mean wave heights, periods and directions for each buoy, as shown in Tables 2 and 3. See Table 2 for the northern site (46022) and Table 3 for the southern site (46051). Bathymetry data was derived from Google Earth ©2009. From this data, frequency, the wavenumber, wave energy and the wave vector components were all calculated.

The model functioned by solving ray theory equations on a 2D lattice. The energy and wavenumber of waves entering the model from the defined boundary conditions were based on the gathered wave data. At each grid point the incoming energy and the k and ℓ values (x and y vector components of the wavenumber values, respectively) and depth were used to calculate the group velocity and thus the convergence of wave energy into a given location, allowing a new energy level to be determined at that point. As the energy propagated through the model each new grid point's calculations were based on the previous point's energy level and the convergence of propagating energy into that point. This process was iterated until the energy front (wave front) had passed through the model and become stable (i.e. the energy approaching the shore became constant at every point). The stabilization is expected because the boundary conditions on energy and wavenumber were held fixed as the values typical for each month.

Table 2

Buoy Number 46022			
Month	Wave Height (m)	Period (s)	Dominant Wave Direction (degrees)
January	3.1	13.0	287
February	3.1	12.9	295
March	2.9	12.5	305
April	2.4	11.3	308
May	2.1	10.0	316
June	2.0	9.4	317
July	1.8	8.8	302
August	1.6	9.0	316
September	1.9	9.9	315
October	2.3	11.3	301
November	2.9	12.4	303
December	3.2	13.2	299

Mean wave data by month for buoy number 46022 describing the mean wave height, mean period and dominant wave direction.

The wave energy converters were simulated based on their size and a percentage of incoming energy at each grid point extracted. The outgoing energy from each grid point was unaffected by the WEC and was based solely on the group velocity and the energy contained within that grid point. The energy extracted was calculated based on energy inflow in the x (k) and y (ℓ) directions independently which optimized the amount of energy extracted. The model was run based on the specifications of the three promising WECs described earlier in this section. The relative dimensions of the WECs can be seen in Table 1. All of the WECs were calculated to extract 15% of the incident wave energy, the estimated maximum according to Previsic and Bedard (2007). Due to functional decisions concerning the grid scale of the model all areal measurements concerning WEC size were calculated to the nearest ten meters. This was done to create a study area large enough to capture any potential effects on the surrounding ocean climate while still rendering the WECs close to the appropriate size. This will serve to over estimate the effects of all three WECs, while the overall efficiency was held constant.

Table 3

Buoy Number 46051			
Month	Wave Height (m)	Period (s)	Dominant Wave Direction (degrees)
January	2.2	11.8	283
February	2.6	13.0	278
March	2.3	13.1	282
April	2.5	11.9	290
May	1.9	10.6	285
June	1.9	9.6	296
July	1.6	10.8	281
August	1.7	9.5	292
September	1.8	10.5	290
October	2.0	11.7	292
November	2.1	11.8	298
December	2.7	12.8	296

Mean wave data by month for buoy number 46051 describing the mean wave height, mean period and dominant wave direction.

The model was based on equations from Chapman and Malanotte-Rizzoli [1989] and implemented by Baylor Fox-Kemper for a slowly varying homogeneous medium. Slowly varying medium in this context means that depth varies on scales larger than a wavelength. If a wave group moves at its group velocity $\vec{c}_g$ then the frequency, *N*, and wavenumber vector, $\vec{k}$, will be determined with respect to time *t,* following the wave group according to the following equations. This is due to the conservative properties of a wave moving through a slowly varying homogeneous medium. The model itself evolves three differential equations that follow the evolution of energy, k and ℓ.

$$\frac{\partial k_i}{\partial t} + \vec{c}_g \cdot \nabla k_i = -\frac{\partial \Omega}{\partial x_i} \quad \text{Equation 1}$$

$$\frac{\partial N}{\partial t} + \vec{c}_g \cdot \nabla k_i = \frac{\partial \Omega}{\partial t} \quad \text{Equation 2}$$

where the position of the wave group is given by

$$\frac{\partial \vec{x}}{\partial t} = \vec{c}_g \left[\vec{k}(\vec{x}, t)\right] \quad \text{Equation 3}$$

Omega (Ω) is the dispersion relation. The energy calculation can be given by the equation $\frac{\partial A}{\partial t} + \nabla(\vec{c}_g A) = 0$ where A refers to the wave action, defined by the energy divided by the frequency $\left(\frac{E}{f}\right)$. An appropriate estimation of wave energy (E) can be found by $\frac{\partial E}{\partial t} + \nabla(\vec{c}_g E) = 0$ where energy is period averaged and proportional to the amplitude for a wave traveling in a slowly varying medium [Chapman & Malanotte-Rizzoli 1989]. In the presence of a WEC this equation was modified so that when *c_ge* was in the incoming direction, a fraction of the incoming energy flux was removed, modeling the WEC energy extraction.

The Excel [Microsoft 2010] code approximates the evolution equation for wavenumber $\vec{k}$ and energy with respect to time and space. The dispersion relation $\Omega = g|k|\tanh(|k|H)$ is used to find the frequency from the wavenumber and depth, and to find the right-hand side of the wavenumber evolution equation and the group velocity $\left(\vec{c}_g = \left(\frac{\partial N}{\partial |k|}\right)\frac{\vec{k}}{|k|}\right)$.

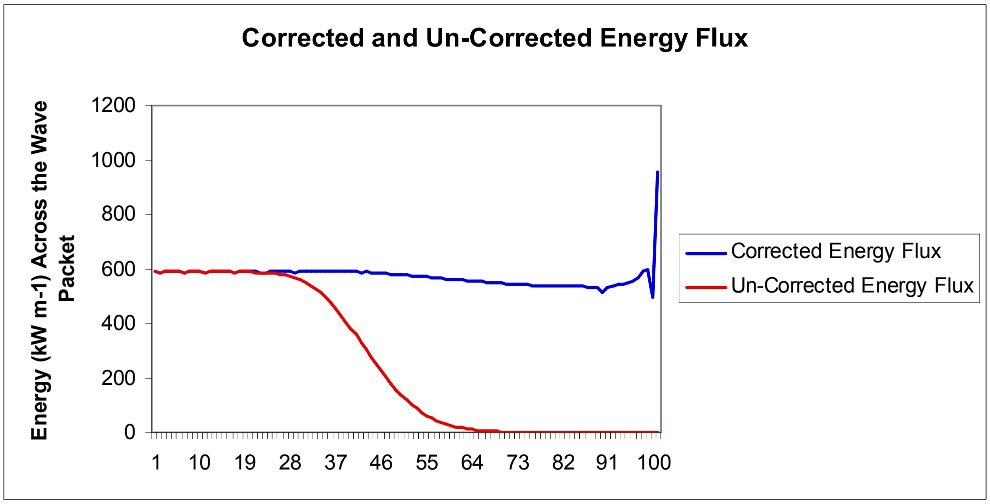
The approximation solution of Equation 1 and the energy conservation equation is carried out by discretizing the model (breaking the model into discrete counterparts in space and time and solving at each point). For the purposes of this study a 10m grid and a 0.1 second time step were used to discretize the equations. For simplicity and numerical stability the derivative of the change in energy is taken with respect to time (Forward Euler time step). This simple discretization is overly diffusive, but as the effects of waves breaking are being neglected by ray theory, this approach handles sudden jumps in energy in a simple way [Fox-Kemper, 2010].

2.4 Overview and Data Analysis

For each model the energy (*E*) was multiplied by the group velocity along the y direction (*Cg_y*). This gives us the flux of energy proportional to the power, propagating past a given point in the x direction for the wave packet. The energy flux should be constant as the wave approaches shore. The control models were run to show a conservation of energy flux with respect to the wave front for all ocean conditions. An example of the control model before and after it has been corrected according to the process explained in the conclusion can be seen in Figures 4. The control group serves to validate the accuracy of the model as a wave front is propagated through it by showing that energy is in fact conserved. It also allows for statistical comparisons to be made to the energy field before and after a WEC has been defined and tested. For the analysis of the results the naturally occurring standard deviation of the energy flux per month was calculated. This was compared to the decrease in energy flux due to the effects of a

WEC. The decrease in energy was reported as a fractional value of the monthly energy flux's standard deviation.

Figure 4



The difference in corrected (blue) and un-corrected (red) energy flux for December for buoy 46022. Notice the decrease in the un-corrected energy flux due to the input of unrealistic zero energy values from the northern edge of the model domain. In the corrected energy flux line the energy flux values along the north and south boundaries are defined and the line becomes much straighter. The straighter line more accurately represents the conservative nature of energy along a ray.

3.0 RESULTS

3.1 Summary of Findings

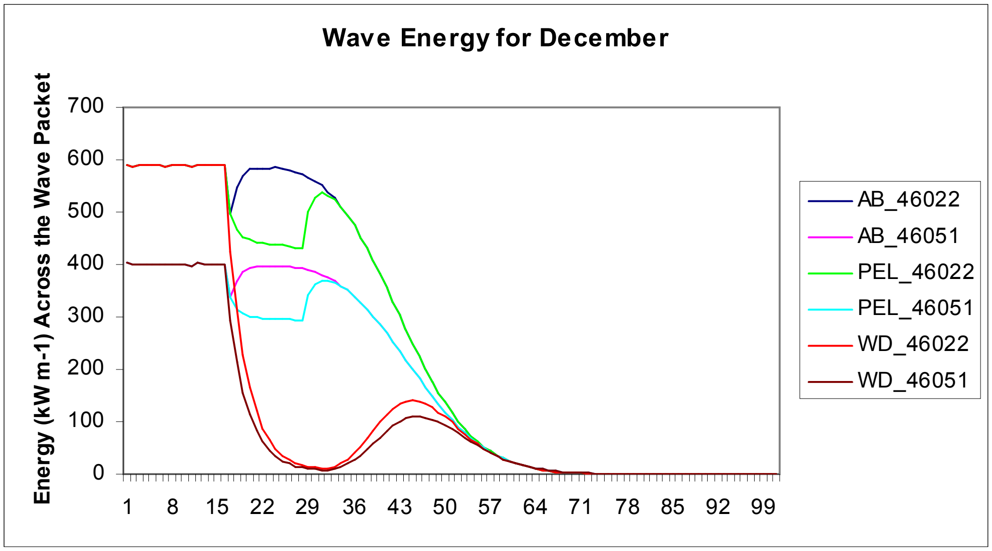
The results of the simulations with the insertion of a WEC showed a decrease in energy on the lee side of the WEC. This decrease varied depending on the size of the WEC, the amount of available energy in the wave front as indicated by mean wave height and the incident wave angle. The distance over which the wave field propagated back into the wave shadow was also affected by the size of the WEC and the direction that the wave front approached from. In short the magnitude of the energy lost was based on the relative size of the given WEC and the available energy. Table 1 looks at the relative size of the WEC's tested.

The graphed lines in Figures 5 and 6 represent the conservation of energy along a ray. According to Chapman and Malanotte-Rizzoli [1989], energy is conserved in a homogeneous slowly varying medium and the line should appear straight as the ray is traced from deep to shallow water. In this model as the wave packet approaches shore the conservation of energy line approaches zero. This is caused by the energy input as defined along the sides of the model. Energy along the edges was originally defined as zero because consistent sidewall boundary conditions were unknown. As the wave packet propagated towards shore the energy along the northern edge of the model began to carry unrealistic energy values of zero into the domain. These values served to decrease the energy as in moved into the model from the north and propagated towards shore. The correction for this is explained in section 4.1 of the conclusion and is visible in Figure 4.

3.2 AquaBUoy

The smallest wave energy converter is the AquaBUoy. As such, it had overall the smallest effect on significant wave height when considering both the northern and southern sites. In December, the energy lost due to the effects of the AquaBUoy was between 0.10 and .31 standard deviations of the monthly wave energy variance. The variation in wave energy for the southern location was between .30 and 1.4 standard deviations of the monthly wave energy variance as calculated from mean swell amplitude. The effects of the AquaBUoy on the propagation of energy for the months of maximum and minimum available energy can be seen in Figure 5 for December and Figure 6 for August, respectively.

Figure 5

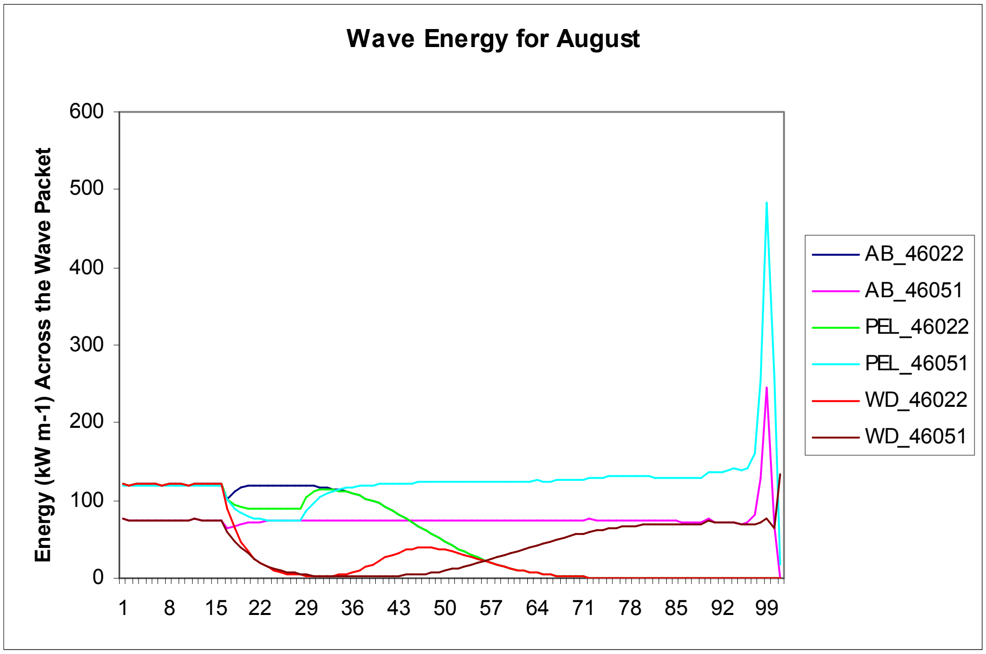


The month with the largest potential energy is December. These graphs are the energy flux for the month of December for all wave energy converters. The wave energy converters are the AguaBUoy (AB), the Pelamis Wave Converter (PEL) and the Wave Dragon (WD). The northern site is 46022, the southern site is 46051. The initial decrease in energy is caused by the given WEC. The second decrease in energy is then caused by the zero value energy inputs in the model domain. The shape of the initial decrease is indicative of the shape of the WEC being tested.

3.3 Pelamis Wave Converter

The Pelamis Wave Converter, while narrow is much longer than the AquaBUoy. The design of the Pelamis Wave Converter allows energy extraction to occur for its entire length. The difference in size is apparent in the length of the decrease in wave energy flux in Figure 5 for the month of December and Figure 6 for the month of August when compared to the AquaBUoy. The Pelamis Wave Converter also showed only a slight decrease in significant wave height and energy. For the northern location, the decreases in energy lost due to the effects of the Pelamis Wave Converter were between 0.30 and 1.88 standard deviations of the monthly wave energy variance. For the southern test location the difference in wave energy flux was between .30 and 2.26 standard deviations of the monthly wave energy variance.

Figure 6



The month with the smallest potential energy is August. These graphs are the energy flux for the month of August for all wave energy converters. The wave energy converters are the AguaBUoy (AB), the Pelamis Wave Converter (PEL) and the Wave Dragon (WD). The northern site is 46022, the southern site is 46051. The initial decrease in energy flux is caused by the WEC being tested. The second energy decrease (when applicable) is caused by the zero value energy inputs into the model domain. The shape of the initial energy decrease is indicative of the tested WEC. As the wave packet approaches shore the amplitude increases rapidly as the model does not account for the energy dissipation caused by waves breaking.

3.4 Wave Dragon

The largest wave energy converter tested was the Wave Dragon and it had the largest effect on the wave field. To model this device it was assumed that all energy falling between the deflecting arms would be converted into electricity which potentially greatly overestimated the energy loss. For the northern location, the decreases in energy lost due to the effects of the Wave Dragon were between 0.70 and 4.7 standard deviations of the monthly wave energy variance. The range of the decrease in energy lost for the southern location was between .86 and 5.79 standard deviations. The decrease in wave energy along the wave packet for the Wave Dragon can be seen in Figure 5 for December and in Figure 6 for August.

4.0 CONCLUSION

4.1 Correction to Model

In Figures 5 and 6 the energy along the wave packet decreases as it approaches shore when it should be conserved. This is because the wave energy is not defined along the entire length of the model and therefore as rays are followed into the model there are certain locations where there is zero energy being added to the model. This energy decrease is reflected by the approach angle of the wave packet. The more northern the mean wave direction the sooner the energy decrease occurs. It is these energy inputs of zero that lead to the decrease in energy. The solution to this problem comes from running the model again to define the energy at the locations along the north and south boundaries of the model. The energy along the southern edge of the model is used as it does not see the effect from the input of zeros from the northern edge. These values are then used to define the energy input along both boundaries and the model is run again with energy values defined along the western, northern and southern boundaries. When the model is re-run the line, representing the conservation of energy, becomes straight as is visible in Figure 4.

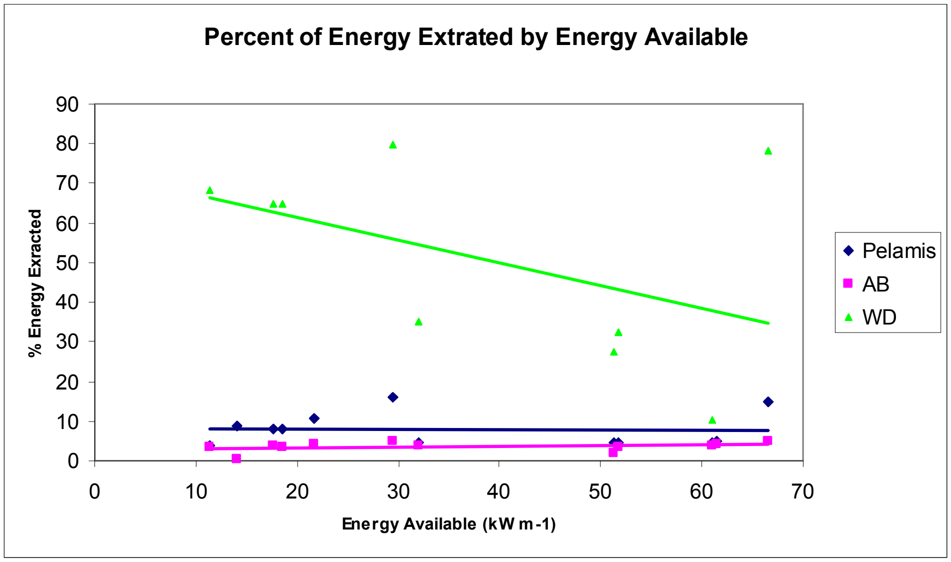
4.2 Discussion of Results

It is important to note that the systematic reduction of power across all wave climates is different than seasonal changes in wave power which are due to seasonal and local weather patterns. The systematic reduction of available power would affect all wave climates equally. This has the theoretical potential to decrease the standard deviation of the available energy across all wave climates, regardless of season. While the results of this study show that the decrease in energy is not significant given the standard deviation of available energy in a given month, a comprehensive decrease in wave energy for all wave climates may or may not have negative effects on ecological, environmental or economical processes driven by wave climate. Additionally, the standard deviation of waves in a given month is likely much larger than that reported by NOAA and visible in Tables 2 and 3, due to the effects of local storms and other weather variations not captured in an estimate based on monthly mean wave fields.

Based on the results of this study, it is apparent that in most cases the effects of a wave energy converter on the wave climate in a given location will be small, being less than the naturally occurring standard deviation of wave energy in a given month. Based on the variance in wave energy for the majority of wave climates it can be reasonably hypothesized that the effects of a pilot wave energy converter would be negligible on near shore processes such as long shore sediment transport as well as recreational ocean users such as surfers for most ocean climates.

For the Pelamis Wave Converter and the AquaBUoy the relationship between percentage of available energy extracted and total available energy is roughly linear with a slightly negative slope for December (Figure 7) and for August (Figure 8). This can be partially attributed to the relative significance that the percentage of energy extracted has on wave climates when less energy is available. As the amount of available energy increases a 15% energy decrease becomes a less significant energy loss.

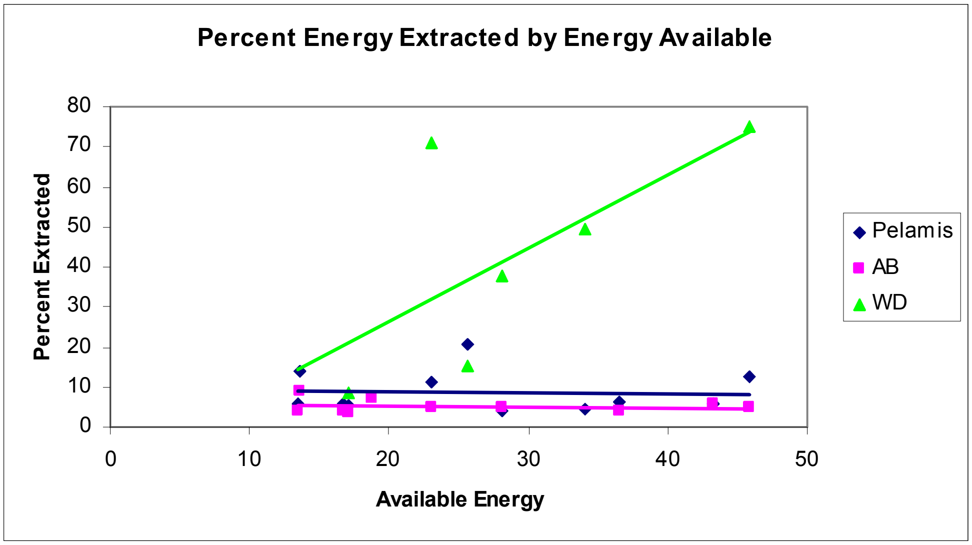
Figure 7



The percentage of energy extracted by total available energy for a given WEC across all seasons in the northern location. There is a consistent pattern for both the AquaBUoy (AB) and the Pelamis Wave Converter (Pelamis) of a linear and slightly negative relationship between the available energy and the percent extracted. The relationship for the Wave Dragon (WD) is not consistent between the northern and southern locations, likely attributed to the input of zero energy values in the model domain.

This is confirmed in the analysis of the monthly standard deviation of available energy. As available energy decreases, the variance in monthly available energy decreases and therefore a (relatively) smaller amount of energy loss will have a (relatively) greater significance on the available energy. For the case of the Wave Dragon there is no consistent pattern. This is most likely attributed to the fact that for most wave climates before the wave energy could stabilize across the wave packet the energy field began to feel the effects of the sea bottom where the model begins to lose its effectiveness. Another explanation for the discrepancies in these Figures for all WECs concerned is the effect that the undefined northern and southern energy boundaries had on the incoming energy field.

Figure 8



The percent of energy extracted by total available energy for a given WEC across all seasons for the southern location.

There is a consistent pattern for both the AquaBUoy (AB) and the Pelamis Wave Converter (Pelamis) of a linear and slightly negative relationship between the available energy and the percent extracted. The relationship for the Wave Dragon (WD) is not consistent between the northern and southern locations, likely attributed to the input of zero energy values in the model domain.

Later versions of this model will be run with the model correction in place, giving more accurate data, especially in the case of the Wave Dragon.

4.3 Recommendations

It was found that the environmental effects of a single WEC were minimal for most wave climates. As such it can be recommended that there be an instillation of a single test unit of either a Pelamis Wave Converter or an AquaBUoy in the northern location with little chance of a significant decrease in wave energy for most wave climates. In the southern location, the reported decrease in energy was more significant based on the monthly standard deviation of wave energy. As such, the instillation of a Pelamis Wave Converter or an AquaBUoy would be unlikely to have a significant effect on wave climate except in summer months when the mean wave amplitude and standard deviation are at their lowest. Based on the above reported results, the instillation of a Wave Dragon has the potential to result in significant decreases in available wave energy for most wave climates. This is especially true in the summer months where mean wave amplitude and standard deviation are at their lowest.

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