Nov 17th, 11:50 AM - 12:20 PM

A Transient Model for Wave Energy Resource Assessment on the West Coast of Vancouver Island (Session Paper)

Clayton E. Hiles
Triton Consultants Ltd.

Bradley J. Buckham
The University of Victoria

Michael R. Tarbotton
Triton Consultants Ltd.

AXYS Technologies Inc.

A Transient Model for Wave Energy Resource Assessment on the West Coast of Vancouver Island

Clayton E Hiles [1], Bradley J Buckham [2], Michael R Tarbotton [1] and Reo Phillips[3]
[1] Triton Consultants Ltd., Vancouver, BC
[2] The University of Victoria, Victoria, BC
[3] AXYS Technologies Inc., Sidney, BC

Abstract— Numerous studies have shown that one of the most energetic wave climates in the world exists off the West Coast of Vancouver Island. Yet this resource has yet to be tapped for the generation of significant quantities of renewable electricity. Successful implementation of wave energy converters will require an intimate knowledge of this vast resource. Not only does the resource guide initial demonstration deployments, it is needed to inform long term planning including possible redesign of electricity transmission infrastructure to accommodate 100's of MW of ocean wave power. Most knowledge of the wave climate in this area is derived from course-resolution studies which have focused on the ocean outside the continental shelf, but wave energy converters will likely be sited close to shore. This paper describes the construction and validation of an unstructured SWAN wave model covering the continental shelf on the West Coast of Vancouver Island. This model is driven by wave and wind boundary conditions sourced from FNMOC and COAMPS models respectively. Validation to several near-shore buoys shows that the accuracy of the model is equal to that of the boundary conditions. No significant error appears to be introduced by the SWAN calculations. Presented in this paper is the average wave energy transport for the year 2010. Though still in development, this model can be used today as tool for understanding the wave climate on the West Coast of Vancouver Island.

1. Introduction

Global wave energy inventories [1,2] have shown that the West Coast of Canada possesses one of the most energetic wave climates in the world, with 40-50kW/m on average at the continental shelf. With this energetic climate there is an opportunity to generate significant quantities of renewable electricity through the use of wave energy conversion (WEC) technologies. Despite this opportunity, little work has been performed to quantify the resource with precision.

Resolving the spatial distribution of the wave resource, especially near-shore, is a critical step to enable wave energy development. Utilities such as BC Hydro require knowledge of the resource so that they can effectively plan infrastructure development such as transmission lines. Proponents of wave energy developments require detailed wave resource data to ensure demonstration sites are energetic, evaluate designs a priori and ensure project viability.

Previous studies of the Western Canadian coast have focused either on the off-shore wave climate [3], or on small sections of coastline [4,5]. The present work details the development of a wave model covering waters from the continental shelf to the shore-line of the West Coast of Vancouver Island (see Fig. 1), and over a 450km stretch of British Columbia and Washington coastline.

This model leverages publicly available off-shore wave data to estimate wave conditions within the continental shelf at high resolution. The model is under development inside the West Coast Wave Initiative (WCWI) which endeavors to monitor wave conditions along the Vancouver Island coast on an ongoing basis. The present paper concentrates on the setup and validation of the model, but also includes an estimate of average wave energy transport through an entire year.

Section 2 reviews other wave models used in support of the wave energy industry. Section 3 discusses the setup of the model and the input data sources including bathymetry, wave and wind boundary conditions. Section 4 covers the validation of the model to buoy measurements made in 2010. Section 5 discusses the model results, including the yearly average wave energy transport.

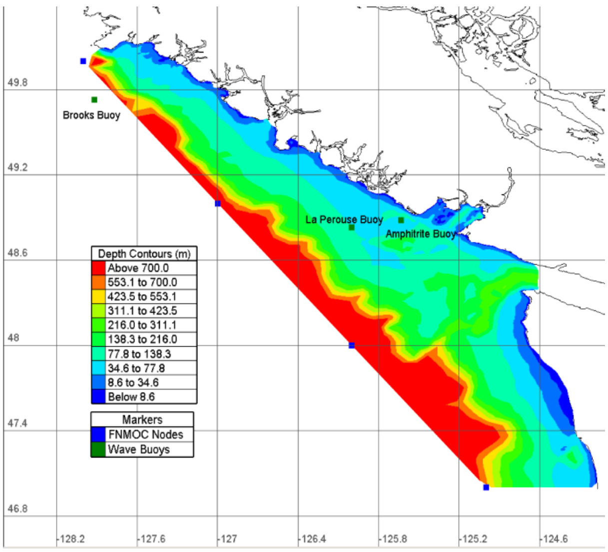

Figure 1 - Map showing BC/WA coastline. Color contours give depth throughout model domain. Green squares indicate wave buoy location. Blue Squares indicate FNMOC data nodes used for model boundary conditions.

2. Wave Modeling for the Wave Energy Industry

Effective development of wave energy resources requires quantification at high spatial and spectral resolution. High spatial resolution is required to identify areas where wave energy naturally concentrates due to geographic factors. These will likely be the areas where wave energy extraction is most economical and spatial detail in a near-shore model allows them to be efficiently prospected.

High spectral resolution is required so that the performance of a wave energy conversion (WEC) technology may be accurately evaluated. Though buoys can provide the necessary spectral resolution, they cannot provide sufficient spatial resolution. An effective and economical method to get the necessary resolution with sufficient spatial detail is to use a computational model to estimate wave conditions.

Canada, the UK, Ireland and other countries have each developed wave atlas' [5,6,7]. These studies inventory the wave resources off-shore of the respective nation based on the parametric results of course resolution ocean-scale wind-wave models. Though these types of studies are necessary to provide an initial understanding of the wave climate and provide justification for further study, they are severely limited by the wave data they use.

Ocean-scale wind-wave models are usually limited in resolution and use software which does not accurately estimate wave conditions in shallow water where bathymetry significantly effects wave propagation. The results of global wind-wave models are usually parameterized in terms of *significant wave height* (H_{m0}) and *peak period* (T_p). These parameters are convenient for many applications but full wave spectra are required for accurate estimation of WEC device performance. These limitations require a more detailed near-shore model be used.

Near-shore wave models employ specialized software to estimate wave conditions in shallow water. One of the most widely used software packages is Simulating WAves Nearshore (SWAN) [8]. This software is able to account for the most important wave physics near-shore, and computations may be made on an irregular triangular mesh of variable resolution. This allows grid resolution to be increased in those areas with decreasing water depth, thus ensuring small-scale variations in wave energy are only evaluated when needed.

Near-shore wave resource models have been developed for regions in Portugal [9], Spain [10] and Canada [4]. Each of these studies each uses ocean-scale model results to drive a near-shore SWAN model operating in structured mode. The Portuguese model is fully transient, covers the countries coastline, has a number of nested sub-domains to provide detail in areas of interest[9]. The Spanish model covers only a small part of the coastline in the Galicia region and is used to study near-shore conditions for a small number of frequently occurring boundary conditions [10]. The Canadian model covers a small section of the coastline of the West Coast of Vancouver Island around the Ucluth Peninsula. Near-shore wave conditions are calculated for a large array of boundary conditions and from these results a continuous history of near-shore conditions were interpolated to construct a time-series spanning 2002 to 2007[4].

The WCWCP model documented in this paper covers the continental shelf of the West Coast of Vancouver Island. An unstructured grid is used to maintain computational efficiency while retaining high resolution where required, eliminating the need for nesting. Boundary conditions are sourced from an ocean-scale wind-wave model and the model is run in transient mode. Using buoy data collected within this region this paper will show that this model is able to accurately hind-cast wave conditions close to shore at high spatial and spectral resolution.

3. Model Setup

In this section, the setup of the model including mesh construction, boundary condition selection and SWAN source term settings are discussed.

3.1. Unstructured Grid

Within the domain of the model, the depth ranges from approximately 1000m at the continental shelf to zero depth at shore. In the deep water, a large grid spacing is sufficient; in shallow near-shore water the grid spacing must be much small to capture the small scale wave transformations that occur due to interaction with the ocean floor.

An unstructured grid was constructed using TriGrid2, an in-house advancement on the public domain TriGrid grid generation software [11]. Grid spacing was specified proportional to water depth with a lower limit on spacing of 75m. The proportionality constant was determined though convergence analyses that considered change in H_{m0} as a metric for convergence [12]. During development of the grid there were several locations where poor resolution of sharp changes in bathymetry caused spurious wave results in SWAN. To address these problem areas, the resolution of the grid was manually increased in each location using the editing tools included in TriGrid2.

3.2. Bathymetry

Bathymetry was interpolated onto the computational grid from a source bathymetry TIN (triangulated irregular network) maintained by Triton Consultants Ltd. The variable resolution bathymetric TIN contains 280,000 nodes soundings at variable resolution. It was constructed from bathymetry surveys sourced from Canadian Hydrographic Service and the National Oceanographic and Atmospheric Administration.

3.3. Wave boundary conditions

There are a number of sources of publicly available wave data for the Eastern Pacific. Unfortunately directional wave measurements appropriate for wave boundary conditions are not available for the West Coast of Vancouver Island. The best alternative is results from ocean-scale wind-wave models.

Sophisticated ocean-scale operational models are operated by a number of institutions world-wide, including the Fleet Numerical Meteorology and Oceanography Center (FNMOC). FNMOC uses the Wavewatch3 modeling software [13] and published results that are appropriate as boundary conditions to the near-shore wave model. Table 1 gives some information on the spatial and temporal resolution of the FNMOC global model.

Table 1 – Basic resolution model information.

	FNMOC Global
Grid Spacing	1N x 1E
Run Frequency	12hr
Forecast Frequency	3hr

3.3.1 Local Validation

Local validation of the FNMOC model was performed through comparison to wave parameters measured near the model boundary. Three wave buoys were deployed in the region of interest during 2010. The large platform Brooks and La Perouse ODAS buoys are deployed permanently and maintained by Environment Canada. The Amphitrite buoy is a smaller 2m ODAS buoy that was deployed by the West Coast Wave Collaboration Project, a precursor to the current WCWI. The location of each buoy is given in Fig. 1. Basic buoy details are given in Table 2.

Table 2 - Basic buoy details.

Buoy	Type	Location	Sample Period	Deployed (2010)
Brooks	AE	-127.92E,49.73W	1hr	Jan-Dec
La Perouse	AE	-126.00E,48.83W	1hr	Jan-Dec
Amphitrite	TR	-125.63E,48.88W	1hr	Apr-Oct

The Brooks buoy is closest to the SWAN model boundary along which the FNMOC data is applied, and so, the FNMOC data was validated at that location. Fig. 2 gives the measured and modeled H_{m0} and T_p for the month of January 2010. H_{m0} is very well correlated. The correlation of T_p is acceptable, but not excellent. This is expected as T_p is an unstable parameter which may jump from one spectral peak to another. The clustering of the buoy data at specific values indicates the frequency binning scheme used by the buoy. For quantitative statistics comparing the FNMOC data to the Brooks buoy see Section 4.1.

3.4 Spectral Shape

Parametric FNMOC wave data were used to construct the spectral boundary conditions of the model. The WAFO Matlab toolbox [14] was used to synthesize directional spectra with the JONSWAP spectral shape and directional spreading from parametric wave data.

For the synthesis of each JONSWAP spectrum, the peak-enhancement factor, γ, was specified based on a fitting of the JONSWAP spectral shape to the spectrum measured at the Brooks Buoy. Peak width parameters σ_a, σ_b were set at their default values of 0.07 and 0.09 respectively. Spectra are specified at locations: -128E 50N, -127E 49N, -126E 48N, -125E 47N (see Fig. 1); SWAN interpolates the spectra between these points.

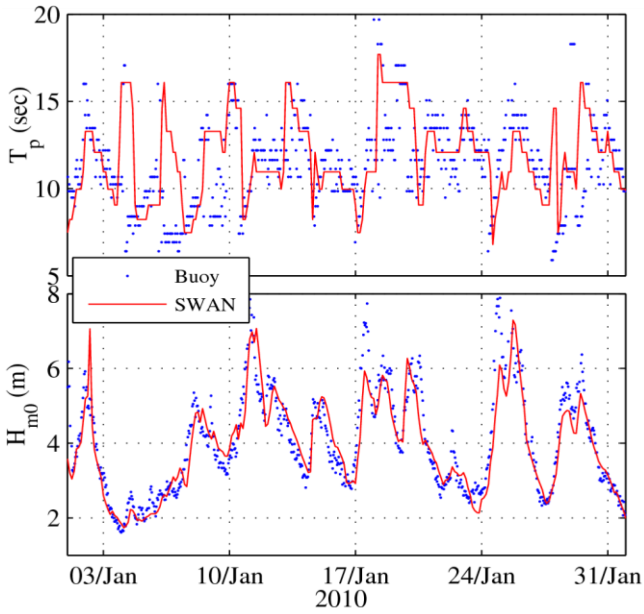

Figure 2 - Comparison of T_p and H_{m0} at the South Brooks Buoy, January 2010.

3.5 Local Wind Boundary Conditions

Local wind conditions were obtained from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model. Though there are many regional wind models, the COAMPS model results were selected for their high spatial resolution (0.2° x 0.2°), coverage of both ocean and land and the native output of the model at 10m altitude. SWAN requires that driving winds be equivalent to 10m altitude; native output at 10m means that no scaling is required. In addition, the COAMPS wind model is used to drive the FNMOC regional wave models. Below the COAMPS Eastern Pacific model results are locally validated against measurements at the La Perouse and South Books buoys in Table 3.

Throughout this paper parameters *bias* (B), *scatter index* (SI), and *correlation coefficient* (r) are used to quantify the accuracy of model results in comparison to measurements. Bias is the systematic difference between the data-sets, scatter index is the root-mean-square difference divided by the mean measured value (e.g. $SI=E_{rms}/\overline{U}$) and correlation coefficient is a measure of the correlation between the data with r=1 being perfect. *Pairs* refers to the number of time-periods that were compared and an *overbar* indicates a mean value.

Table 3 gives the validation statistics for the COAMPS wind speed (U) over the year of 2010. Wind speed is compared to measurements made at the La Perouse and South Brooks buoys. The bias at both buoys is relatively low, but the scatter index is high. This indicates that on average the model is accurate, but there is often significant error in individual events. This is also indicated by the correlation coefficient, which is acceptable at ~0.6, but is not indicative of highly correlated results. This level of accuracy is expected for a wind model when comparing it to point measurements.

Table 3 - Validation statistics comparing COAMPS model results to measurements at La Perouse and South Brooks buoys.

	Pairs	$\bar{U}$	B	*SI*	r
La Perouse	2819	6.61	-1.5	0.61	0.60
South Brooks	2801	7.99	1.29	0.47	0.64

3.6. Water Level and Currents

Initial testing showed that the model has little sensitivity to water levels and currents at the magnitudes typical within the vast majority of the domain [12]. Because these factors influence the wave estimates so little, they are not included in the model in the current stage of development. If during development they are deemed to be reasonably important at specific locations very near-shore they may be included in the future. Water levels and currents may be obtained simply from harmonic constituents derived from an ocean circulation model such as [15], or more accurately, by running a transient ocean circulation model in concert with the SWAN model.

3.7 SWAN Software Setup

The model uses SWAN version 40.81 with COAMPS/FNMOC wind/wave boundary conditions. It is executed in non-stationary mode at a 3 hour time-step (the same as the boundary condition data). The model was setup using the options given in Table 4. All un-noted options were left as default.

Table 4 - SWAN model setup.

Option	Value
Computational grid	UNSTRUCTURED
Wind-growth/whitecapping	WESTH
Bottom Friction	On (defaults)
Stopping criteria	Defaults with: NPNTS=95, MXITNS=40

4. Model Validation

The model was run for the 2010 calendar year. Preliminary testing showed that SWAN's WESTH wind-growth/whitecapping option to have the best performance. This section evaluates the performance of the model by comparing model results to wave measurements made by the two buoys at La Perouse and Amphitrite Bank. The wave boundary conditions are evaluated by comparison to the Brooks Wave buoy.

4.1. Wave Parameters

Presented in Fig. 3 and 4 are the SWAN parameters T_p and H_{m0} compared against values obtained from the La Perouse and Amphitrite buoys respectively.

Fig. 3 is presented for January 2010 and shows good agreement for T_p and excellent agreement for H_{m0}. In the winter months the wave conditions in the area are typically dominated by swell, so model agreement in-line with that of the wave boundary conditions is expected.

Fig. 4 is presented for August 2010 and shows reasonable agreement for both T_p and H_{m0}. In the summer months wave conditions in the area are often dominated by locally generated wind waves, so model accuracy in-line with the accuracy of the wind boundary conditions is expected.

Tables 5 and 6 give the parameters B, SI, and r for the entire year of 2010 at each wave buoy for T_p and H_{m0} respectively. The statistics for the FNMOC model compared to the Brooks buoys are also included as an indicator of the boundary condition accuracy.

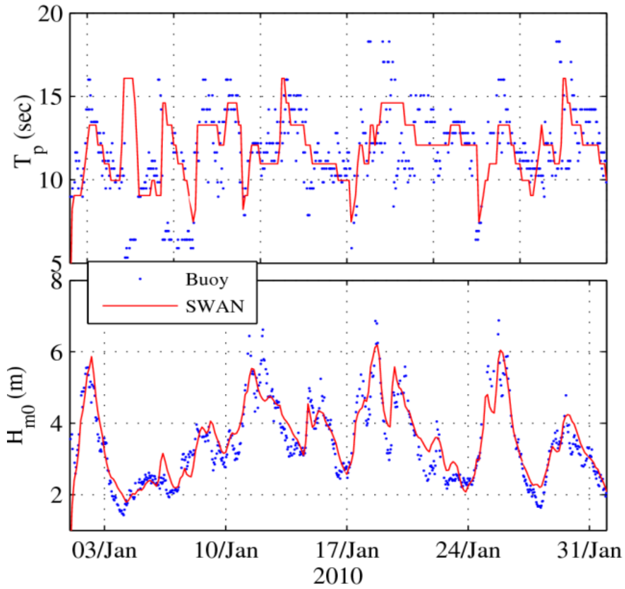

Figure 3 - Comparison of measured and modeled and at the La Perouse Buoy, January 2010.

Table 5 shows that at both wave buoy locations the accuracy of the model in estimating is excellent. At the Perouse buoy the model has equal r and lower |B| and SI than the wave boundary conditions. At the Amphitrite buoy, 80km shore-ward of the off-shore wave boundary, the model has only slightly lower r and higher SI. The bias amplitude, |B|, at the Amphitrite buoy is very low at 2mm.

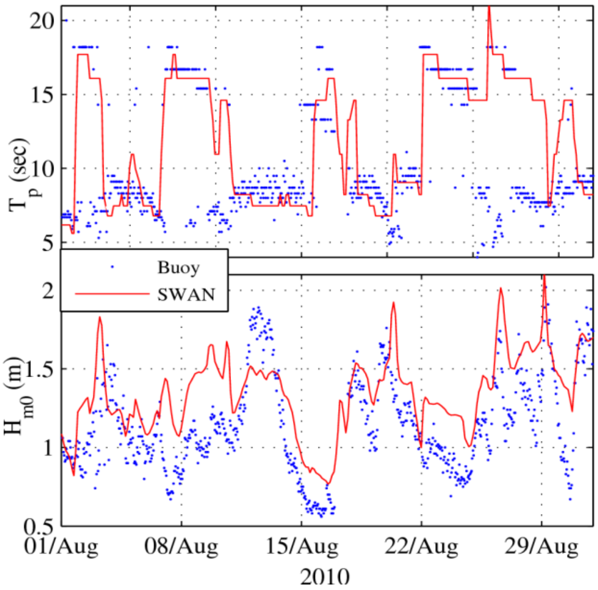

Figure 4 - Comparison of measured and modeled T_p and H_{m0} at the Amphitrite Buoy, August 2010.

Table 5 - Statistics comparing measured and modeled.

Buoy	Pairs	H_{m0}	B	*SI*	r
Brooks	2712	2.94	-0.13	0.18	0.94
La Perouse	2920	2.50	0.03	0.17	0.94
Amphitrite	1370	1.69	-0.02	0.22	0.91

Table 6 - Statistics comparing measured and modeled.

Buoy	Pairs	T_p	B	*SI*	r
Brooks	2712	10.62	0.75	0.31	0.32
La Perouse	1475	10.48	0.54	0.28	0.46
Amphitrite	1370	10.16	0.87	0.34	0.47

4.2. Wave Spectra

Though a detailed validation of the modeled wave spectra is beyond the scope of the current work, it is worth presenting some representative results here, as the strengths and weaknesses of the model can be further revealed in spectral evaluation.

Wave spectra are presented here in terms of frequency (f) in Hz, and variance density (S) in m^2/Hz. Figure 5 compares the measured and modeled spectrum at the La Perouse buoy at 09:00 Jan 2, 2010. In this example the spectra has a single swell peak at 0.075Hz and the model replicates it with good accuracy. The T_p estimated by SWAN (13.3sec) is very close to the measured value (13.5sec).

Fig. 6 compares the measured and modeled spectrum at the Amphitrite buoy 13:00 Aug 6, 2010. The measured spectrum has a distinct double peak, one at 0.06Hz and the other at 0.16Hz. The low frequency peak is likely from swell originating from the Southern Ocean. Because boundary condition spectra are synthesized using a single peak JONSWAP shape, this model cannot accurately reproduce spectra with multiple swell peaks.

This model can, however, reproduce spectra with multiple wind-sea peaks provided those seas are generated by wind action within the modeled domain. Fig. 7 shows one such instance at the Perouse buoy 15:00 Jan 14, 2010. This spectrum has swell peak at 0.7Hz a wind-sea peak at 0.16Hz and a minor secondary swell peak at 0.03Hz. In this case the model has replicated not only H_{m0} and T_p (5.0m compared to 4.8m and 12.1sec compared to 14.2 sec), but it has also given a good estimate of the wave spectrum over the primary swell and wind peaks.

To improve the model performance in instances of double peaked swell spectra, refinement of the wave boundary conditions would be necessary. This may be achieved by employing a multiple peaked spectral shape for synthesis of boundary spectra, or by obtaining spectral boundary condition data.

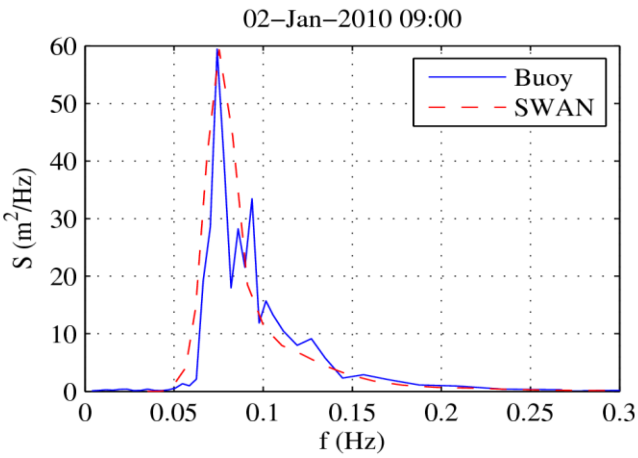

Figure 5 - Measured and modeled wave spectra at La Perouse buoy, 09:00 January 2, 2010

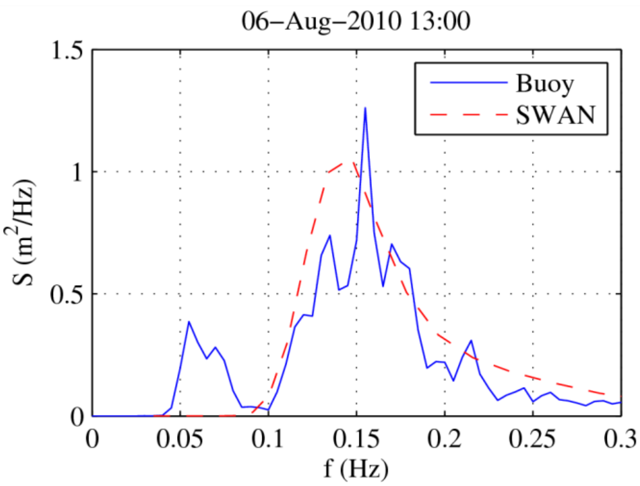

Figure 6 - Measured and modeled wave spectra at Amphitrite buoy, 13:00 August 6, 2010.

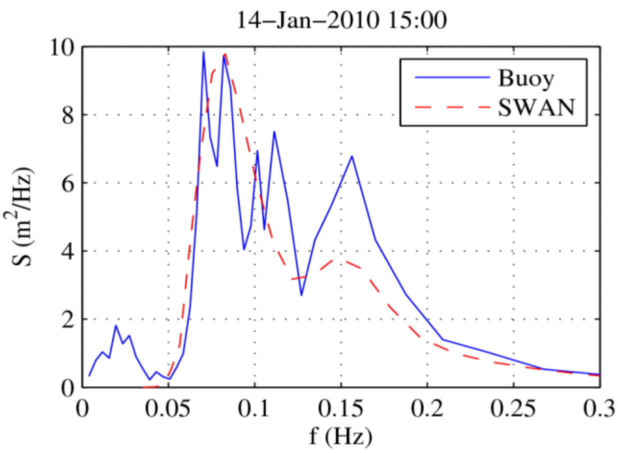

Figure 7 - Measured and modeled wave spectra at the La Perouse buoy, 15:00 January 14, 2010.

FNMOC provides wave height and period parameters for the swell and wind-sea spectral partitions corresponding to the WAM [16] spectral partitioning scheme [17]. It may be possible to use this parametric data corresponding to specific partitions of the wave spectra to synthesize a multi peaked spectrum at the off-shore boundary but, initial efforts to have yielded poor results.

5. Results

When 'prospecting' for potential wave energy development sites, the wave parameter most of interest is *wave power transport* (J). This parameter represents the total energy in the sea per meter of wave front and may be calculated for a discrete wave spectrum as follows:

$$J = \rho g \sum_i S_i C_g(f_i, h), \qquad (1)$$

Where i represents the frequency dimensions of the spectrum, C_g is the group velocity and h is the water depth.

Fig. 8 gives the mean wave energy transport, $\bar{J}$, for the year 2010 over the entire computational domain. Like previous course-resolution studies [1-3], $\bar{J}$ is approximately 45kW/m along the continental shelf. This study, however, reveals significant spatial variation in $\bar{J}$ close to shore.

Of interest to wave energy developers are areas where wave energy naturally concentrates close to shore due to wave interactions with the ocean floor. These sites are desirable because high energy waves can be accessed without lengthy (and costly) transmission cables. One such site is Amphitrite Bank, approximately 7km from the coastal community of Ucluelet, BC - this is the location that the WCWCP deployed the Amphitrite wave buoy.

Fig. 9 is a close-up of Fig. 8 in the area around Ucluelet and Amphitrite Bank. The presence of the Bank concentrates wave energy by refracting the waves towards one another like a lens. Based on the model results, $\bar{J}$ for the year 2010 is 38kW/m at a distance of roughly 7km from shore. The average J measured by the Amphitrite buoy during its deployment (April-October) was 20.1kW/m. The average J given by the model over the same period was 20.0kW/m. This result provides confidence that the model is accurately capturing the wave energy focusing which occurs around Amphitrite Bank.

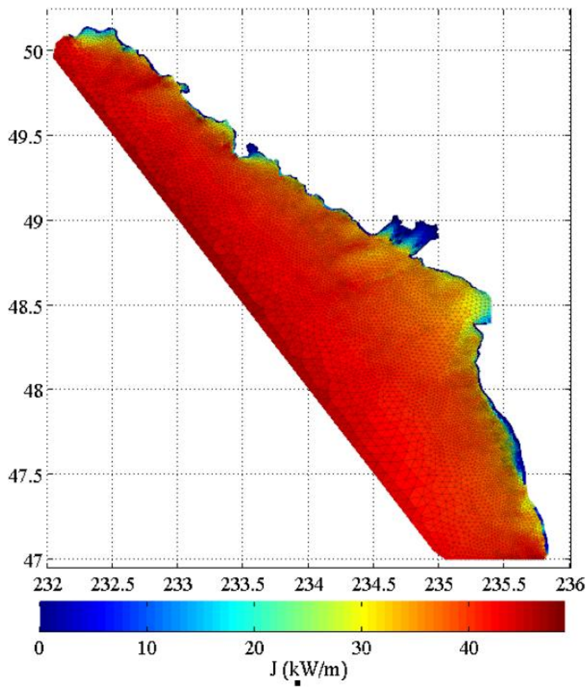

Figure 8 - Mean modeled wave power transport for the year 2010.

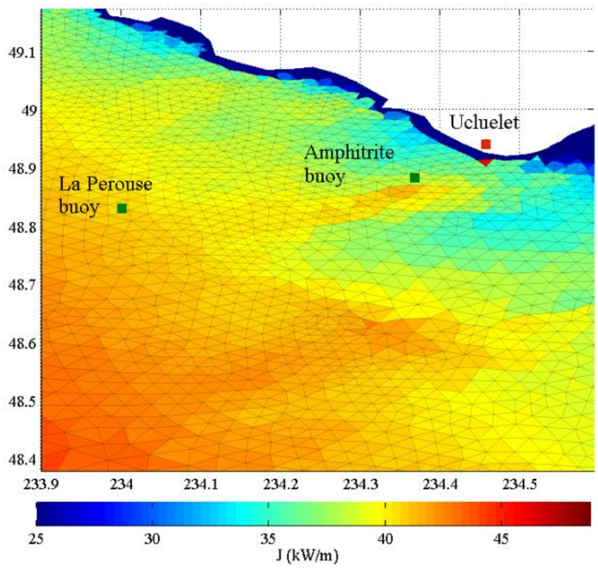

Figure 9 - Mean modeled wave power transport for the year 2010 around Amphitrite Bank.

6.0 Conclusions and Future Work

Global and national wave energy inventories have shown that off the West Coast of Vancouver Island is one of the most energetic wave climates in the world. In response to the wave energy community's need for more detailed wave data close to shore, a near-shore wave model was developed for the continental shelf west of Vancouver Island. This model uses the SWAN wave modeling software in unstructured mode and wind and wave boundary conditions sourced from the COAMPS and FNMOC wave models respectively. The output from the model has high spatial resolution close to shore and high spectral resolution everywhere in the modeled domain.
The model was validated by comparison with T_p and H_{m0} measured at two wave buoys within the domain. With almost no calibration, the correlation coefficient r for H_{m0} at each buoy is greater than 0.9. For T_p the r at each buoy is greater than 0.45. In terms of T_p and H_{m0} the model is approximately as accurate as the driving boundary conditions.

A full validation of wave spectra was not performed, but a few representative results were examined. In cases of spectra where a single swell peak was measured, the model was able to reproduce the spectrum quite accurately. Where there is a single swell peak and a locally generated wind sea was observed, the model has acceptable accuracy but did not fully capture the wind-sea. Where two swell peaks were measured, the model could not accurately reproduce the spectrum.
Issues with multiple peaked spectra arise in this model because the wave boundary conditions are constructed based on T_p and H_{m0} and a single peaked JONSWAP spectral shape. In the future, the accuracy of the model could be increased by utilizing a double peaked spectral shape, or by securing a source of spectral boundary conditions.

The model has yet to be validated in terms of wave direction. Though many wave energy converters are omni-directional in nature, validation of wave direction should be performed to ensure the robustness of the model.

The model detailed in this work requires further development, but even at this stage it has been shown that it accurately predict the wave parameters and T_p and H_{m0}. Future uses of the model will include the generation of a hind-cast covering 2002-2011 and wave forecasting.

7. Acknowledgments

The principle author gratefully acknowledges financial support from the West Coast Wave Initiative and Triton Consultants Ltd.

8. References

[1] A. M. Cornett, A global wave energy resource assessment, in: proceedings of the 18th international offshore and polar engineering conference, ISOPE, Vancouver, Canada, 2008.
[2] G. Mork, S. Barstow, A. Kabuth, M. T. Pontes, Assessing the Global Wave Energy Potential, ASME Conf. Proc. 2010 (49118) (2010) 447–454,
[3] A. Cornett, Inventory of Canada's Marine Renewable Energy Resources, Tech. Rep. CHC-TR-041, National Research Council - Canadian Hydraulics Centre, Ottawa, K1A 0R6, Canada, 2006.
[4] A. Cornett, J. Zhang, Nearshore Wave Energy Resources, Western Vancouver Island, B.C., Technical Report CHC-TR-51, Canadian Hydraulics Centre, 2008.
[5] C. Hiles, B. Buckham, P. Wild, Wave Energy Resources in Hesquiaht Sound, in: Proceedings of the Canadian Society for Mechanical Engineering Forum, 2010.
[6] ABP Marine Environmental Research Ltd, Atlas of UK Marine Rewable Energy Resources: Technical Report, Tech. Rep., ABP Marine Environmental Research Ltd, 2008.
[7] ESB International, Accessible Wave Energy Resource Atlas : Ireland : 2005, Tech. Rep., Marine Institute, Sustainable Energy Ireland, 2005.
[8] N. Booij, R. Ris, L. Holthuijsen, A third-generation wave model for coastal regions. 1. Model description and validation, Journal of Geophysical Research 104 (C4) (1999) 7649–66
[9] G. Iglesias, R. Carballo, Wave energy and nearshore hot spots: The case of the SE Bay of Biscay, Renewable Energy 35 (11) (2010) 2490–2500
[10] E. Rusu, C. Guedes Soares, Numerical modelling to estimate the spatial distribution of the wave energy in the Portuguese nearshore, Renewable Energy 34 (6) (2009) 1501–1516
[11] R. F. Henry, R. A. Walters, Geometrically based, automatic generator for irregular triangular networks, Communications in Numerical Methods in Engineering 9 (7) (1993) 555–566,
[12] C. Hiles, On the Use of Computational Models for Wave Climate Assessment in Support of the Wave Energy Industry, Master's thesis, The University of Victoria, 2010.
[13] H. Tolman, The numerical model WAVEWATCH: a third generation model for hindcasting of wind waves on tides in shelf seas, Communications on Hydraulic & Geotechnical Engineering - Delft University of Technology 89-2 (1989) .
[14] P. Brodtkorb, P. Johannesson, G. Lindgren, I. Rychlik, J. Rydén, E. Sjö, WAFO - a Matlab Toolbox for the Analysis of Random Waves and Loads, in: Proc. 10'th Int. Offshore and Polar Eng. Conf., ISOPE, Seattle, USA, vol. 3, 343–350, 2000.
[15] M. Foreman, W. Crawford, J. Cherniawsky, R. Henry, M. Tarbotton, A high-resolution assimilating tidal model for the northeast Pacific Ocean, Journal of Geophysical Research 105 (C12) (2000) 28629–51
[16] S. Hasselmann, K. Hasselmann, E. Bauer, P. Janssen, G. Komen, The WAM model-a third generation ocean wave prediction model, Journal of Physical Oceanography 18 (12) (1988) 1775–810
[17] P. Wittmann, Personal Communication, 2010.