ASSESSMENT OF FAST SPECTRAL WAVE TRANSFER METHODOLOGIES FROM DEEP TO SHALLOW WATERS IN THE FRAMEWORK OF ENERGY RESOURCE QUANTIFICATION IN THE CHILEAN COAST

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Alternative wave transfer methodologies from deep to shallow water that aim at reducing the computational time in cases where the full propagation of a large number of wave climates is often prohibitive are defined and tested against full spectral propagation using complex measured wave climates. A proposed method is presented in this work which is able to accurately reproduce the shape transformation of directional spectra while significantly reducing the computational time. Another transfer method is also validated, which can achieve relatively good results when there is no spectral information and only statistical wave parameters (e.g. significant wave height, peak period and mean wave direction) are available. Finally, an application of the proposed method in the framework of energy resource quantification in Chile is presented.

Keywords: wave modeling, wave propagation, wave transfer, spectral reconstruction, parametric reconstruction

INTRODUCTION

The coast of Chile is often affected by a mixture of swells, originated by storms in both northern and southern hemisphere, and local wind seas, resulting in complex spectral distributions for wave climates (SHOA 2011). Thus, for studies of coastal nature, full spectra wave propagation from deep to shallow water is the preferred option to be considered since methods based on wave statistics and standard parametric spectral forms could severely bias the estimation of wave climate and the associated energy resource.

Full spectral propagation of wave climates is the most suitable approach when multi-modal spectral distributions are frequent. However, in engineering projects, the full propagation of a large number of wave climates from deep to shallow waters often requires a prohibitive amount of computational time that justify the definition of alternative approaches aimed at reducing the number of spectral wave propagations (e.g. Fassardi 2004; Groeneweg, van Ledden and Zijlema 2006).

In order to avoid full spectral propagation, in this work we propose and validate a full spectral reconstruction method for the central coast of Chile that significantly reduces the number of required wave climate propagations from deep to shallow water in the model. The method is based on the propagation of synthetic narrow-band one-meter height spectral distributions mapped over of the entire frequency-direction space which are then used to recompose the hindcast spectra at specific shallow water locations (~15 m depth) by simple mathematical means. Thus, transferring of a real full deep-water spectra to shallow waters, involves solving a least square problem to find the coefficients that allow the reconstruction of the associated shallow water spectra as a combination of the propagated synthetic unit spectra.

The method is tested confronting its performance against full spectral model propagation, using for this purpose measured wave data collected during 4 months in Lebu, Chile (37.6° S, 73.7° W) by means of a Triaxys buoy in deep water (150 m depth) and a synchronous ADCP in shallow water (15 m depth) to characterize the propagated swell characteristics. For the validation, six representative wave spectra are selected from the data using the Maximum Dissimilarity Algorithm (Camus et al. 2011).

The proposed method is also compared with an alternative reconstruction approach based solely on wave statistics, which has been currently applied in the Chilean context, where information on full wave spectral data is not commonly available and only wave parameters such as significant wave height, peak period, and mean wave direction exists (e.g. Nicolau del Roure 2004).

For the propagations of the synthetic and the full spectra, the SWAN spectral wave model (Booij, Ris and Holthuijsen 1999) is used.

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METHODOLOGY

Wave propagation from deep to shallow water is many times dominated (can be approached) by linear processes. In such cases, wave height in shallow waters can be estimated as a proportion of the wave height in deep water that depends only on its incident direction and period. The same is true for the wave direction, which will also depend on the incident direction and period in deep water (independent of the wave height). In the case of the peak period, the linear wave theory implies that it remains unchanged. Additionally, the linearity assumption makes it possible to transform each wave component of a complex sea state independently and then to put it back together by linear superposition. All these considerations allow the definition of alternative propagation methods, in which the wave transformations are done only once for each combination of direction and period and then, by using the linear principles, any given wave climate can be transformed in a fast and effective way to shallow water.

In order to fast-transfer waves from deep to shallow waters, two different methods have been defined depending on the type of transformation they apply: the Parametric Reconstruction Method and the Spectral Reconstruction Method.

The Parametric Reconstruction Method acts only on statistical wave parameters (e.g. significant wave height, peak period and mean direction) and therefore, its results are also wave parameters. This method has been used in the Chilean context (e.g. Universidad de Valparaiso 2009) and a description can be found in literature (e.g. Fassardi 2008; Nicolau del Roure 2004).

The Spectral Reconstruction Method on the other hand is able to transform directional spectra, and the results come also in the form of spectra. Although this method is known to be used by engineering consultancies, there is no information available in literature that indicates how the transformation is done and how the method is validated. Moreover, there could be multiple approaches to this problem being used at this time. Therefore, in this work, we propose and validate a method of this type which is robust and consistent.

A more detailed explanation of both methodologies is given below.

Parametric Reconstruction

The parametric reconstruction method consists on transforming statistical wave parameters (e.g. significant wave height, peak period and mean direction) in deep water, to their equivalent in shallow water by applying site-specific wave transformation coefficients obtained from pre-modeled scenarios. The steps for applying this method are the following:

1. Build synthetic deep water spectra of H_{m0} = 1 m with different peak periods and directions, covering most of the frequency – direction domain.
2. Propagate these spectra independently in the model and get the resulting wave statistics in the site of interest, in order to construct the wave transformation coefficients (1) and (2).

$$C_H = f(T_{\text{deep water}}, D_{\text{deep water}}) \quad (1)$$

$$C_D = f(T_{\text{deep water}}, D_{\text{deep water}}) \quad (2)$$

Where,
C_H: Significant wave height transformation coefficient.
C_D: Mean wave direction transformation coefficient.
$T_{deep\ water}$: Peak or mean period in deep water.
$D_{deep\ water}$: Mean wave direction in deep water.

3. Apply equations (3), (4), and (5) to the wave parameters in deep water to find the corresponding parameters in shallow water:

$$H_{\text{shallow water}} = H_{\text{deep water}} \times C_H(T_{\text{deep water}}, D_{\text{deep water}}) \quad (3)$$

$$D_{\text{shallow water}} = C_D(T_{\text{deep water}}, D_{\text{deep water}}) \quad (4)$$

$$T_{\text{shallow water}} = T_{\text{deep water}} \quad (5)$$

In cases where the desired wave period and direction in deep water doesn't exactly match a propagated period – direction pair, a bilinear interpolation of the wave transformation coefficients is applied.

Spectral Reconstruction

Although different approaches may exist, the proposed spectral reconstruction method consists on constructing the target shallow water spectrum by linearly combining already transformed synthetic spectra using the same coefficients that construct the real deep water spectra as a linear combination of the synthetic deep water spectra. The steps for achieving this are the following (a summary is shown on Figure 1):

1. Build synthetic deep water spectra of H_{m0} = 1 m with different peak periods and directions, covering most of the relevant frequency – direction domain.
2. Propagate these spectra independently in the model and get the correspondent synthetic shallow water spectra in the site of interest.

   Then, to transform any given deep water spectrum to shallow waters:
3. Find the coefficients that allow reconstructing the real deep water spectrum as a linear combination of the synthetic deep water spectra. This can be done by fitting each energy bin through the solution of a least square problem.
4. Create the correspondent shallow water spectrum by linearly combining the synthetic shallow water spectra with the coefficients found before.

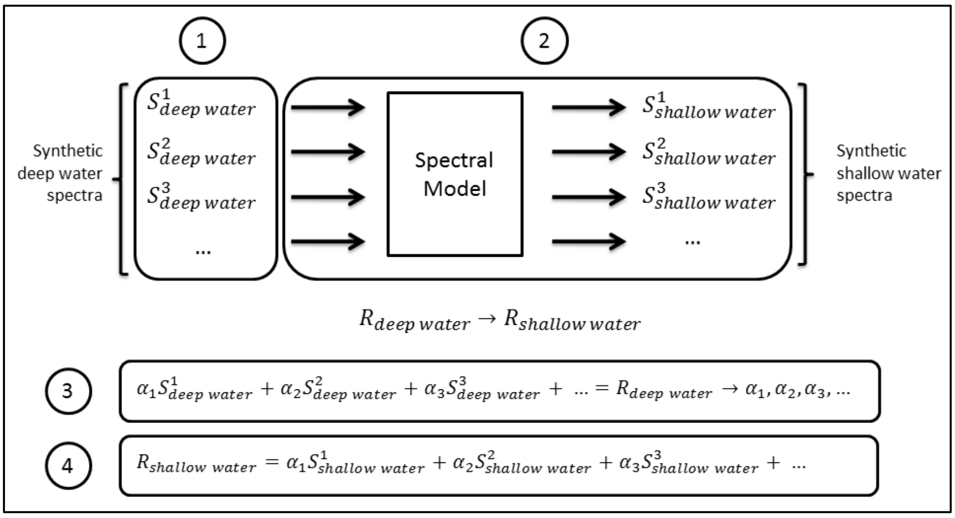

Figure 1: Summary of the proposed spectral reconstruction method.

Note that steps 1 and 2 (which demands more computational effort) have to be done only once for each site, while steps 3 and 4 (which are simple computations) have to be repeated for each real deep water spectra.

It was found that the best results are obtained when coefficients doesn't have a sign restriction (i.e. they can be positive or negative). This can lead to solutions with some negative energy bins, but usually so small that they can be approached to zero without altering the total energy of the spectrum.

The reasons for propagating synthetic spectral distributions instead of doing a bin by bin propagation in the model are: (1) to use a realistic distribution that is consistent with the model physics, and (2) to reduce the required amount of simulations in the model (given that the total number of synthetic spectra should be smaller than the total number of bins).

VALIDATION

The spectral and parametric reconstruction methods were validated using synchronic measured wave data in deep and shallow waters, obtained during a 4 month campaign in front of Lebu, Chile (37.6° S, 73.7° W), in which a Triaxys buoy at 150 m depth and an ADCP at 15 m depth measured wave climates representative of one hour during the whole period (Figure 2). A specific bathymetric survey was conducted on site for modelling purposes.

Figure 2: Location of the Triaxys buoy and the ADCP deployed in Lebu, Chile (37.6° S, 73.7° W)

To test both methods, a comparison was made between the results that came from a direct spectral propagation in the model and the results delivered from the methods. However, because the measuring campaign produced more than 2800 wave climates to model, which, as the framework of this study implies, is prohibitive in terms of computational time, a different approach was used, which consisted on using only a subgroup of wave climates for the comparison, with the condition that the chosen climates had to be very different from one another, in order to test the methods in very dissimilar conditions. This was achieved by applying the Maximum Dissimilarity Algorithm (MDA) (Camus et al. 2011) for the wave climates selection. The MDA is based on the principle of clustering, in which dissimilar wave climates are automatically chosen from a cloud in the height – period – direction space.

After applying this algorithm, 6 wave climates were finally chosen, which are shown in Table 1 and Figure 3. The selected wave climates include a combination of sea and swell from different directions, as well as multi-modal spectra.

Table 1. Statistical wave parameters for the six selected wave climates chosen for comparison

Date UTC	H_{m0} (m)	T_p (s)	MWD (deg)
08-09-2011 14:10	2.50	5.1	314
09-09-2011 21:10	3.37	10.5	253
02-10-2011 21:10	1.65	5.0	204
04-10-2011 12:10	1.12	13.3	282
29-10-2011 08:10	3.44	16.7	230
27-04-2012 17:10	1.75	15.4	225

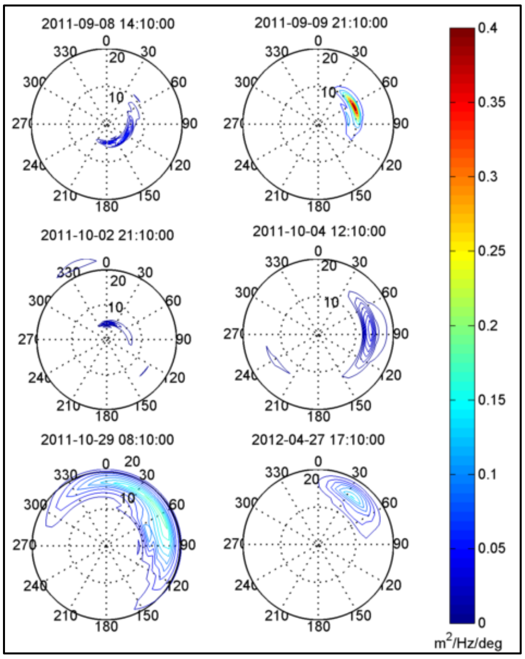

Figure 3: Spectral representation of the six selected wave climates chosen for comparison.

The construction of synthetic deep water spectra for the application of the spectral and parametric reconstruction methods was done using a JONSWAP distribution with its default parameters in the frequency domain (Hasselmann et al. 1973) and a narrow cosine distribution in the direction domain (Goda 2000). The total energy of each spectrum was such that H_{mo} = 1m. To cover the relevant portion of the frequency – direction domain, the spectra were distributed with mean directions between 165° and 360° every 15° and peak frequencies logarithmically spaced between 0.04 Hz and 0.25 Hz, in the form: $f_{i+1} = f_i * 1.1$. This generated a total of 280 synthetic spectra (14 mean directions * 20 peak frequencies).

For the propagation of the synthetic wave spectra and the direct propagation of the 6 selected wave climates, the SWAN wave model was used (Booij et al. 1999), with a 50 m resolution grid.

RESULTS

The results of the direct spectral propagation for the 6 selected wave climates in the study site (Figure 4 and 5) show that the location of the ADCP (red dot in the figures) is protected from waves coming from the SW, and therefore a decrease in significant wave height and a change of direction due to refraction is expected in these cases. Figure 5 shows that the peak period from deep water to the ADCP location is maintained in most cases except in the third one (02-10-2011 21:10), in which the bimodal character of the spectrum (Figure 3) causes one of the components to enter the bay (NW@15s) while the other one not (SW@5s).

Figure 6 shows a comparison between the direct spectral propagation and both reconstruction methods in terms of statistical wave parameters for the 6 test cases. As it can be seen, the proposed spectral reconstruction method delivers excellent results, with little or no difference with the direct spectral propagation in all 3 parameters. The parametric reconstruction method presents relatively good results as well, but with some exceptions, which can be mostly explained by the loss of secondary modes information in multi-modal wave climates. For instance, the large error in terms of peak period and mean wave direction in third case (02-10-2011 21:10) comes from the fact that, as stated before, the third case is a bimodal spectrum, and only the secondary component is able to enter the bay, which is not present in the input deep water wave parameters. This can be avoided if wave parameters of secondary wave components are available, which is not always the case.

The differences in wave parameters between the direct spectral propagation and both reconstruction methods are shown in Table 2, along with the average bias and the root mean square error.

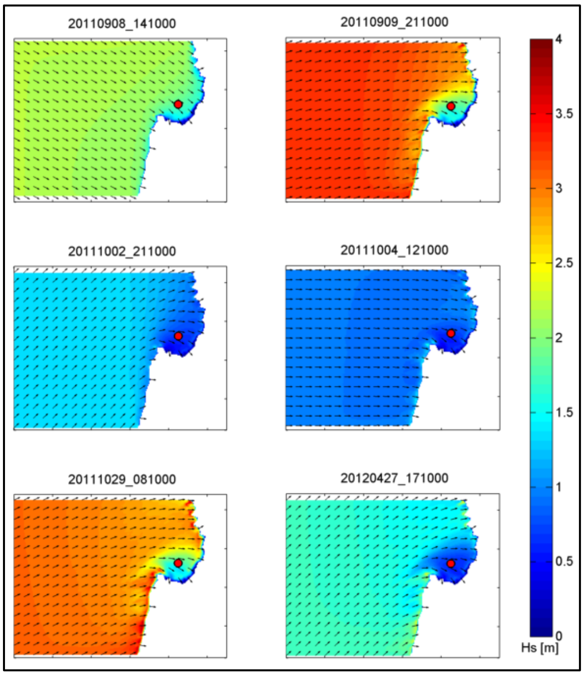

Figure 4: Significant wave height and mean wave direction for the selected climates. The red dot shows the position of the ADCP.

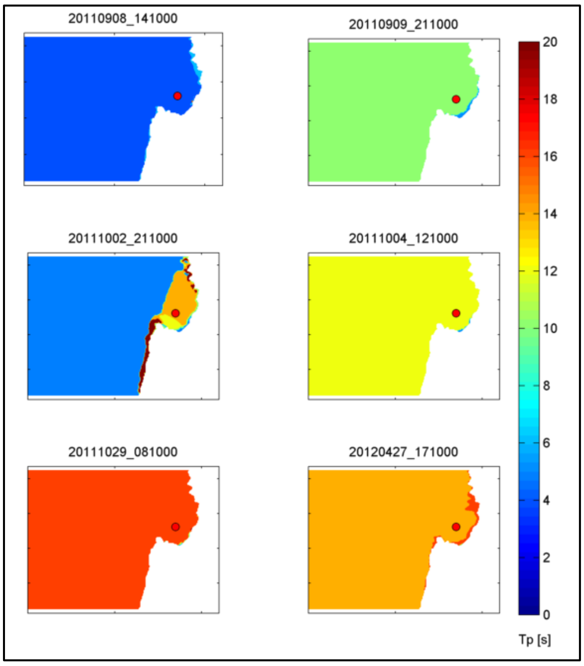

Figure 5: Peak period for the selected climates. The red dot shows the position of the ADCP.

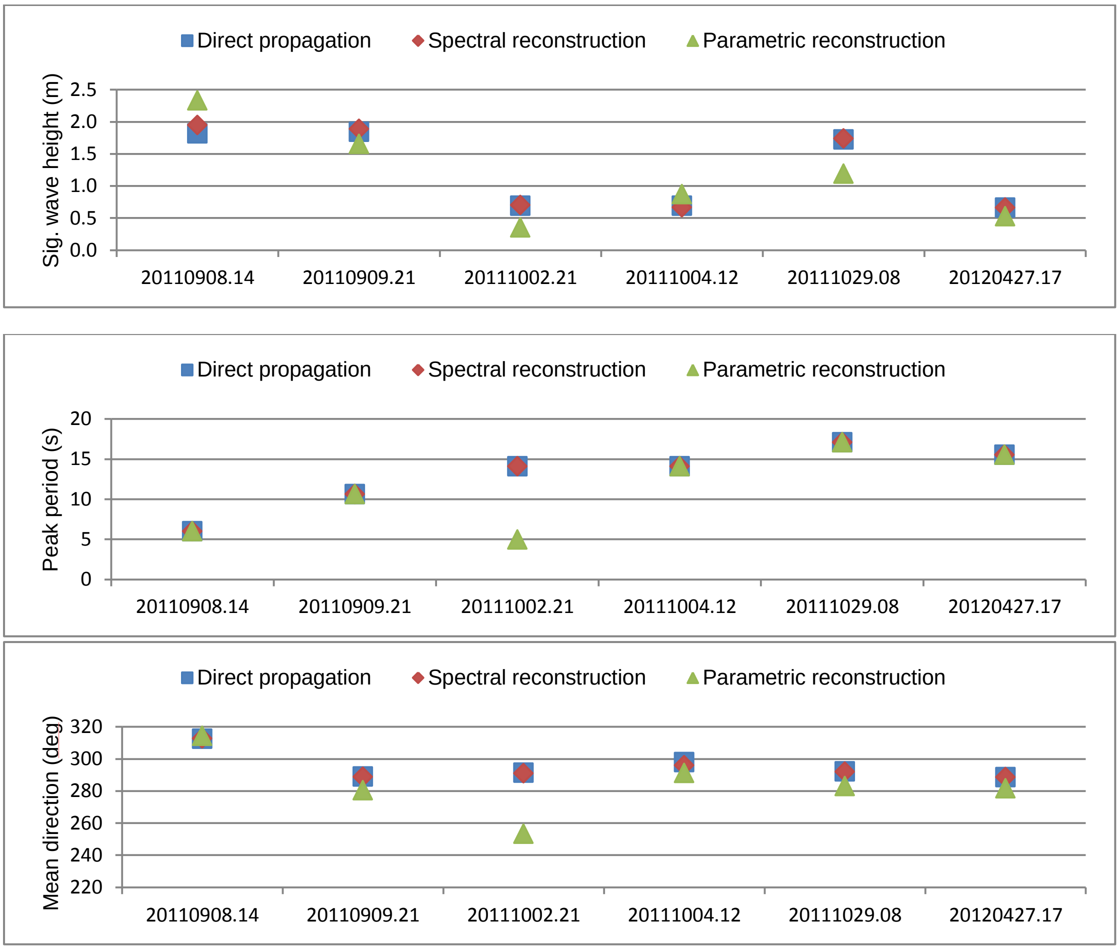

Figure 6: Comparison in terms of wave parameters between the direct spectral propagation and the reconstruction methods for the six selected cases.

Table 2. Differences between the results of the direct spectral propagation and both reconstruction methods for the six selected cases.

	Significant wave height (m)		Peak period (s)		Mean wave direction (deg)	
Date UTC	**Spectral**	**Parametric**	**Spectral**	**Parametric**	**Spectral**	**Parametric**
20110908.141000	0.13	0.51	0.0	0.0	0.1	1.8
20110909.211000	0.04	-0.19	0.0	0.0	-0.3	-8.7
20111002.211000	0.01	-0.34	0.0	-9.2	-0.4	-38.1
20111004.121000	-0.03	0.18	0.0	0.0	-2.0	-6.8
20111029.081000	0.01	-0.54	0.0	0.0	-0.2	-9.1
20120427.171000	0.00	-0.13	0.0	0.0	0.0	-7.1
Average bias	*0.03*	*-0.09*	*0.0*	*-1.5*	*-0.5*	*-11.3*
RMSE	*0.06*	*0.35*	*0.0*	*3.7*	*0.8*	*16.9*

Since the spectral reconstruction method is able to produce spectra, a comparison between the direct spectral propagation and the proposed spectral reconstruction method in terms of spectral distribution was made (Figure 7). The results show that the spectral reconstruction method can reproduce the spectral shape remarkably well, presenting little or no difference with the results of the direct spectral propagation.

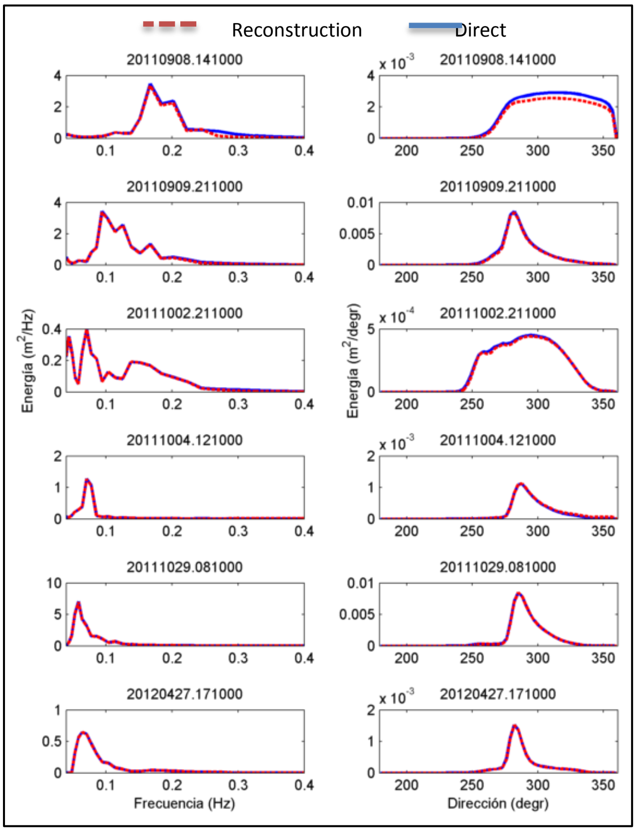

Figure 7: Comparison of the resulting spectra using the direct spectral propagation and the proposed spectral reconstruction method for the six selected cases. Left: spectra integrated in the direction domain. Right: spectra integrated in the frequency domain.

APPLICATION

An application of the proposed spectral reconstruction method is presented for Lebu, Chile, which consists on estimating the differences in terms of wave power between the results of wave modelling from deep to shallow waters (using the Triaxys buoy measurements) and the on-site ADCP measurements. The proposed spectral reconstruction method was applied to the more than 2800 wave climates in deep water obtained during the 4 month of synchronic measurements in Lebu and the wave power was calculated and compared with the wave power calculated from the ADCP measurements (Figure 8).

The results show that in this specific site, there is an overestimation of 36% in the mean wave power (Figure 9), which is mostly explained by an overestimation in wave height. This overestimation is usually favorable in the case of engineering designs because it works on the safer side, but is unfavorable in the assessment of wave energy projects.

Since in this case only 280 simulations were carried out in the model (corresponding to the 280 synthetic deep water spectra) while more than 2800 transformations from deep to shallow waters were done, a reduction of approximately one order of magnitude in computational time was achieved.

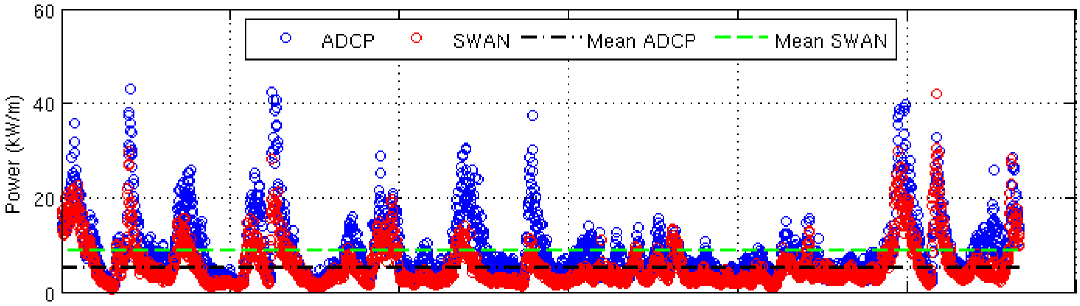

Figure 8: Comparison of the mean wave power time series between the model results and the on-site ADCP measurements in Lebu.

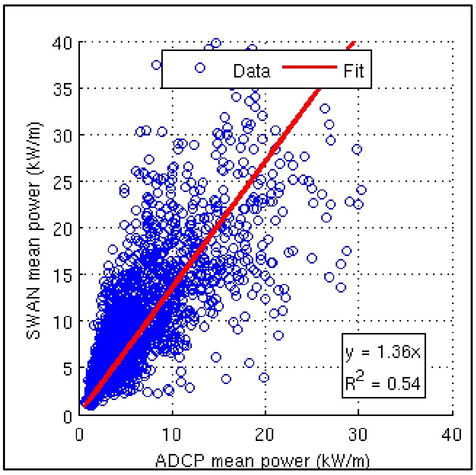

Figure 9: Mean wave power dispersion and linear fitting between the modeled and the measured data in Lebu.

CONCLUSIONS

In cases where wave propagation and transformation is dominated by linear processes (i.e. when non-linear processes are negligible), the application of fast spectral wave transfer methodologies can significantly reduce the computational time required to transfer large number of wave climates from deep to shallow waters, which could be prohibitive otherwise due to the elevated computational cost.

The parametric reconstruction method delivered acceptable results when compared to the direct spectral propagation and its application is justified when only statistical wave parameters are available. Most part of the error comes from the loss of spectral information in multi-modal cases due to the parameterization of the wave climate in a single mode, rather than from the method itself. Wave parameterization including more than one wave component can help reduce this error.

The proposed spectral reconstruction method delivered excellent results in terms of statistical wave parameters as well as spectral shape when compared to the direct spectral propagation in the model.

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