UNIVERSITÀ DELLA CALABRIA
Dipartimento di Difesa del Suolo

DATA ASSIMILATION IN NEAR-SHORE WAVE MODELING

S. Jesús Portilla Y[1]. and Jaak Monbaliu[1]

Abstract: The impact of assimilating buoy directional wave data in nearshore wave modeling is evaluated through hindcasts carried out by means of a nested implementation of the SWAN and the WAM models. The assimilation technique used is an adaptation of the optimal interpolation technique used to a great extent for assimilating wave data. In order to account for complexities of the wave spectrum a partitioning method has been implemented for identifying and separating its different components. The identification of the wave systems in space is done by means of a cross-assignment point to point for the model components. The comparison of components between buoy and model results is also done by cross-assignment. This paper discusses the innovations and limitations involved in the adaptation of the partitioning technique for spectral analysis and points out at the challenges and perspectives of data assimilation in near-shore wave modeling. Some preliminary results of the implementation described are shown. This study aims to improve near-shore wave estimates for the wave climate along the Belgian coast.

1. INTRODUCTION

Wave modeling in near-shore areas is very important for many nearshore and coastal activities. However, the numerical representation of the many processes that take place in shallow waters is still a challenge in wave modeling. In addition, local models rely on the accuracy and the quality of the input data namely bathymetric data, wind field, and wave conditions at the grid boundary.

In general, boundary information is provided to local models either from the output of a coarser regional model or from offshore measurements; both sources having advantages and disadvantages. For the former the model has better spatial distribution output but in general is less accurate than the observations, while for the latter observations are sparser. The use of measurements, which are usually available in nearshore and offshore locations, opens the opportunity for the improvement of the wave boundary conditions required for the local nearshore wave model.

K.U.Leuven, Hydraulics Laboratory, Kasteelpark Arenberg 40, 3001-Heverlee (Belgium)
jesús.portilla@bwk.kuleuven.be

This research was undertaken in order to study the impact of assimilating buoy data in order to improve the wave estimates in the near-shore area. Buoy data could be assimilated in run time as it is done conventionally for operational purposes. However, for the present study the problem of data assimilation is approached in a different way. Buoy data is used to correct the boundary information that is passed from the coarse model grid to the near-shore model grid. The modeling of near-shore waves relies strongly on the boundary conditions, the bathymetry, and the wind data, therefore a significant impact is expected from the enhancement of conditions at the boundary. The model is implemented on a high resolution grid and in addition wind measurements on the grid domain are also available, which opens also the possibility for wind correction.

2. MATERIALS AND METHODS

2.1. Buoy measurements: through the monitoring network of the Flemish Community (Waterways and Marine Affairs Administration), a good number of oceanographic and meteorological observations are available for the Belgian continental shelf. In regard of what it is relevant for this study, directional and non-directional buoy data is available at different locations and depths. In addition, measurements of wind speed and direction from several stations are taken at regular basis.

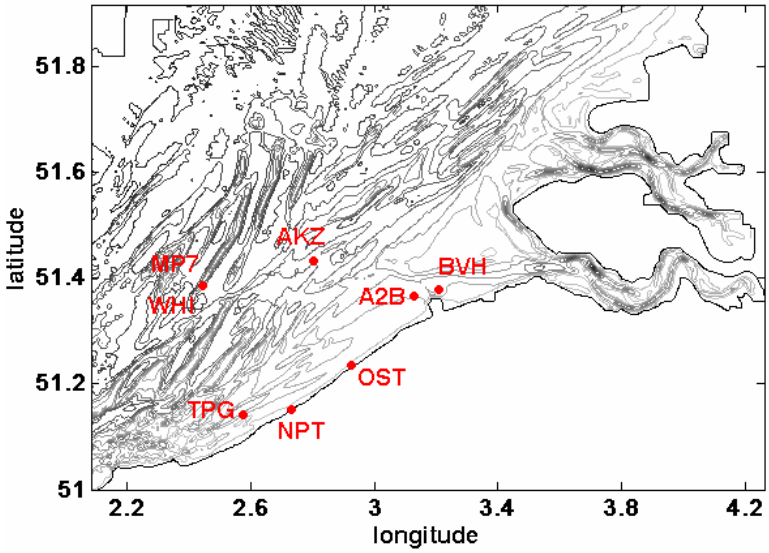


Figure 1 Flemish Monitoring network, measurement locations

The most important measuring locations are indicated in figure 1 with the corresponding description given in table 1. However, for the particular approach of this study and with the aim of evaluating the impact of assimilating offshore buoy data in the near-shore zone, measurements only from the location of Westhinder are considered. The Westhinder buoy is a directional WAVEC buoy which provides information of mean wave energy, mean wave direction and directional spreading for a range of frequencies from 0.005Hz to 0.5Hz with a resolution of 0.005Hz in half hourly basis. Besides, wind records (U_{19}) are taken every 10min from the nearby meteorological station MP7.

Table 1. Measurement locations

Location	Type	longitude	latitude	depth
Westhinder (WHI)	Wavec	2º26'40"	51º23'04"	26.0
Bol van Heist (BVH)	Wavec	3º12'29"	51º22'45"	10.6
Oostende (OST)	Waverider	2º55'39"	51º14'05"	5.7
Akkaert Zuid (AKZ)	Waverider	2º48'09"	51º25'59"	20.5
A2 Boei (A2B)	Waverider	3º07'43"	51º21'57"	8.7
Trappegeer (TPG)	Waverider	2º34'30"	51º08'30"	10.5
Niewport (NPT)	Volter	3º12'06"	51º09'03"	-

2.2. Model implementation: The modeling of waves has been done using a series of four nested grids that gradually converge to the area of interest while resolution is increased. The first three nests at regional scale had been implemented using the third generation WAM-PRO model (WAMDI, 1988, Monbaliu et al., 2000). The coarse model is built to include the entire North Sea, in order to capture swell systems coming from the Atlantic Ocean. The bathymetric data for the coarse grids correspond to the CSM bathymetry (Flather, 1981 and Yu et al., 1990).

Waves in the near-shore area are modeled by means of the SWAN model (Booij et al., 1999) with a high spatial resolution bathymetry of about 250m grid spacing. Wave boundary information can be provided to the SWAN model either from the WAM output or by imposing constant conditions along the boundary similar to those measured at Westhinder.

The winds fields driving the wave models correspond to modeled winds from the United Kingdom Meteorological Office (UKMO) provided every 6h with a grid resolution of 1.25º.

In table 2 the characteristics of the different grids employed for modeling are summarized and in figure 2 the different grid domains are illustrated. Table 3 shows the different model options used in these implementations.

Table 2 Model grid characteristics

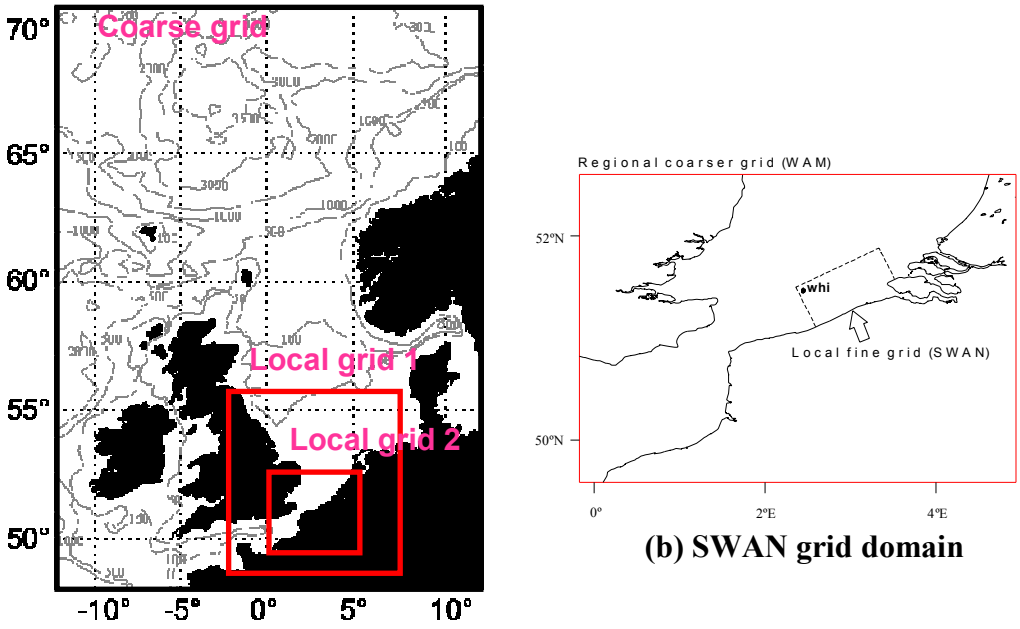
	North Sea		Local1		Local2		BCP SWAN	
RESOLUTION	**(deg.)**	**(Km)**	**(deg.)**	**(Km)**	**(deg.)**	**(Km)**	**(deg.)**	**(Km)**
Latitude resolution	1/3	~36.6	1/15	~7.2	1/45	~2.4	1/450	~0.239
Longitude resolution	1/2	~47.7	1/10	~8.7	1/30	~2.8	1/240	~0.340

COORDINATES	**(deg.)**	**(deg.)**	**(deg.)**	**(deg.)**
North	71.17	55.50	52.63	51.42
South	12.25	48.50	49.23	51.00
Eastern	47.83	9.25	4.75	2.75
Western	-12.25	-2.75	0.05	2.08

COMPUTATIONAL FIGURES				
Prop. time step (s)	600	200	40	-
Grid Size	50x71	121x106	142x154	307x217
Comp. time for 12h	00:01	00:04	00:23	01:04

Table 3 Model options

Parameter	WAM	SWAN
Time step	propagation 10 s source terms 600 s	stationary
Number of directions	12	12
Number of frequencies	25	25
Frequency domain	0.04 - 0.418	0.04 - 0.418
Coordinates	Spherical	Rectangular
Bottom friction dissipation	JONSWAP model	JONSWAP model
Depth induced breaking dissipation	No	No
Wind input	Janssen formulation	Janssen formulation
Wind input time step	6 h	6 h
Whitecapping dissipation	Janssen formulation	Janssen formulation
Snl4 Snl3	DIA No	DIA No



(a) WAM grid domain

(b) SWAN grid domain

Figure 2 Model implementation grids

2.3. The partitioning scheme: The assimilation of buoy data is based on both the schemes of Hasselmann et al., 1996 and Voorrips et al., 1997 developed for the assimilation of spectral components from two-dimensional SAR and from one-dimensional buoy spectra respectively. Both are based on the concept of spectral partitioning proposed by Gerling, 1992.

Following Voorrips et al., 1997 the method for assimilating buoy spectra consists of four different steps: the identification of spectral components (partitioning), the cross assignment of measured and model components, the interpolation of local

information to nearby grid points, and the update of the model spectrum. A detailed description of this procedure is given in the cited reference. Here the attention will be focused on the modifications made to the scheme in order to adapt it for the present application.

Spectral partitioning consists of separating the frequency-direction spectrum into a finite number of significant components based on its morphological characteristics. Each of those components is associated to different wave systems originated from a particular meteorological event. Although the idea of partitioning is relatively simple, its practical implementation has been subject to several adaptations and modifications. The spectral partitioning algorithm, SPA (using Gerling's nomenclature) as such aims to distinguish the different components within the spectrum. However, not all the components are physically significant and posterior merging of components becomes always necessary. It is at that point where the problems arise since the complexity of the spectrum not always allows making a clear evaluation of the significance of the components. Gerling, 1992 proposes a robust method for assessing the significance of components (pattern-extraction algorithm, PEA) considering their persistence not only in time but also in space. He introduces geographical, temporal, and spectral threshold parameters with the remark that those parameters are expected to be application dependent. Moreover a remark is made on the fact that it doesn't appear possible to obtain completely satisfactory results just based on parameterization and inspection of a human operator is required. This last constrain makes the scheme unfeasible for automated applications.

With the purpose of using the concept of partitioning for data assimilation, Brüning et al., 1994 and Hasselmann et al., 1996 reviewed both the partitioning and the combining procedures. That partitioning algorithm is based on the watershed concept and is more cost efficient than Gerling's scheme, although the partitioning results are expected to be the same. For the combining of partitions Hasselmann et al., 1996 do not consider the time and space persistence of the components which reduces the robustness of the scheme. The combining is performed according to spectral distance, contrast, and energy content between partitions by means of threshold parameters that are subject to calibration. Although this way of merging components appears consistent and more straightforward, one has to be very cautious with the use of this scheme, because the final partitioning results are very sensitive to the threshold parameters. Besides, those parameters appear to be data set dependant and the order in which the combining criteria is applied seems to play a role as well.

Hanson and Phillips, 2001 have implemented Hasselmann's scheme for developing software for identifying and tracking wave systems (WITS). Instead of prescribing parameters, Hanson and Phillips, 2001 prefer to set up a procedure for their optimization. The attention is drawn to the fact that yet those parameters are dependant on several factors like local wave climate, spectral resolution and instrumentation type. A number of remarks about the threshold factors for combining and cross-assigning partitions using this scheme is also given by Aarnes and Krogstad, 2001.

So far there is not an ideal procedure to asses the significance of the different components. Therefore, in order to make proper use of the partitioning technique a specific set up for combining components is recommended depending on the particular application. For the present adaptation of the method, the spatial

persistence of components is going to be considered, but the temporal persistence will not be taken into account. On the other hand, none of the previously described methods will be used, and yet another implementation is going to be proposed.

In order to avoid the introduction of several parameters to which the scheme is very sensitive, an intermediate smoothing step has been introduced to carry out the combining task. It has been noticed that this procedure combine correlated components in a more natural way than by using threshold values; first noisy components are merged and then partitions that are less significant. The parameter required for this procedure is the final number of partitions that are considered significant for each specific application. The strength of smoothing is determined implicitly by the initial state of the spectrum (complexity, noise level, etc.), its resolution, and the final number of partitions expected. The type of filter employed is a low pass filter achieved by means of 2D convolution of the spectrum matrix and an incidence filter matrix of order three. In summary, spectrum is smoothed and then partitioned in a loop of iterations that end when the prescribed number of partitions is reached. In figure 3, an example of this implementation is given; in (a) the 2D spectrum is shown, (b) is the result of the smoothing and (c) shows the partitions found. For this example the number of final partitions has been set to two.

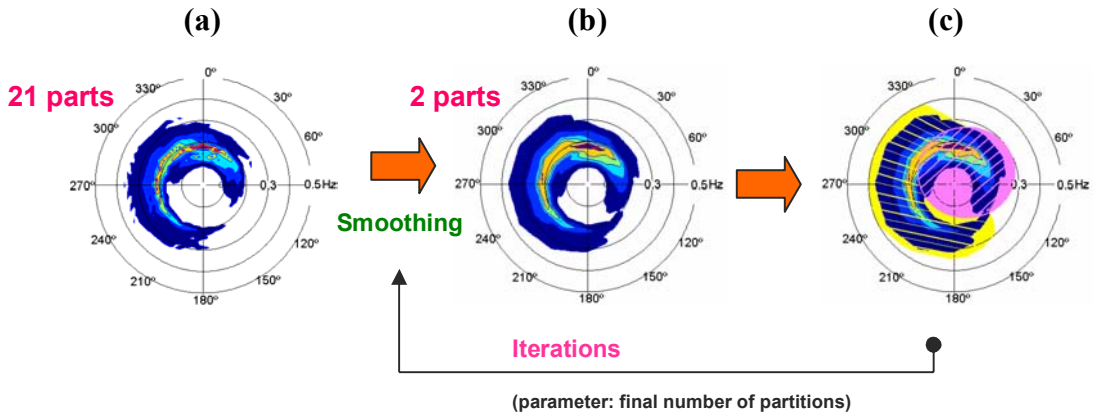


Figure 3 Implementation of the partitioning technique

2.4. Cross-assignment of partitions: for the purpose of comparison and also for assimilation, after partitions have been determined in the model and measured spectra, components have to be cross-assigned in order to find corresponding pairs. In the ideal situation, each component of the measured spectrum should correspond one in the model spectrum. This in practice is not always the case, in some situations there are more components present in one of the sources than in the other and even if the total number of components is equal, the discrepancy in energy, frequency, and direction might be very large.

In Hasselmann et al., 1996 the cross-assignment is done calculating the relative distance (normalized square distance) between components in the wave number space. Two pairs are cross-assigned when they are closest to each other. Components that are beyond a critical threshold value are left for further combining or rejection.

In the implementation of this method, some inconsistencies were found regarding mainly the use of the normalized square distance as criterion. The algorithm has the

tendency to combine components from one source with components on the other source that are located towards the high frequencies. For this reason the criterion has been changed to evaluate directly the distance in frequency and direction of components and cross-assign pairs that are closest. It would be also desirable to have an idea about the degree of the correspondence between the different cross-assigned pairs, for that purpose, a set of different classes has been established based in frequency and direction windows that determine the range of distance in which that pair has been cross assigned. In table 4 these classes are defined, showing the colors they have been given for the scatter plots of figure 5.

Table 4 Cross-assignment classes definition

		Fre. window	Dir. window
CLASS 1	Very well correlated	0 - 0.01	0 – 30º
CLASS 2	Well correlated	0.01 – 0.1	0 – 30º
CLASS 3	Less correlated	0.01 – 0.1	0 – 90º
CLASS 4	Non correlated	0.1 – 0.5	0 – 180º
CLASS 5	Without pair	-	-

For the analysis of the evolution of the spectrum along the domain, it is advantageous to have an idea on how different wave components are varying spatially due to bathymetric effects (refraction, bottom friction dissipation, depth induced breaking, …). In this regard, the implemented cross-assignment procedure comprises two parts. The first part refers to a cross-assignment model to model. The model spectrum from a given boundary point (starting from the extremes) is cross-assigned with the spectrum from its closest boundary point that is also closer to the buoy output location. This cross-assignment chain is closed at the boundary point that is closest to the buoy output location, where boundary point spectrum and spectrum at the model buoy location are also cross-assigned. The second part is a cross-assignment between spectrum from the model buoy location and spectrum from the buoy measurements. This structure allows having a clear identification of the different model components along the entire boundary and also a clear cross-assignment between model and measurements. This has been illustrated in figure 4.

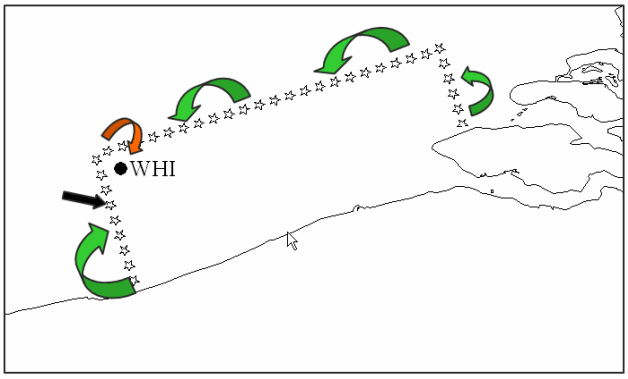


Figure 4 Illustration of the cross-assignment method

3. PRELIMINARY RESULTS

Regarding the update of the boundary spectrum using buoy measurements there are many possibilities and challenges. Here, the optimal interpolation method used by Lionello et al., 1992 and Voorrips et al., 1997 is going to be considered.

An interesting characteristic in the approach of Lionello et al., 1992 is the distinction made for different states of the spectrum relative to the wind forcing. The states considered are wind sea growth under time-limited conditions, decay in absence of wind, and mixed systems produced in situations of sudden change in wind direction. For the first case, power relationships (of dimensionless energy as function of dimensionless time and dimensionless energy as function of dimensionless mean frequency) are fit to numerical results, and then the correction is made under the assumption that the errors in the wave prediction can be mainly attributed to errors in the wind stress field. For the second case, the correction is approached considering that the average steepness of the first guess and corrected spectrum should stay constant, following the study Lionello and Janssen, 1990. For mixed systems, a separation of wind sea and swell is advised to estimate the correct wind duration, the correction is made only for the wind sea component with the same assumptions made for the first case situation.

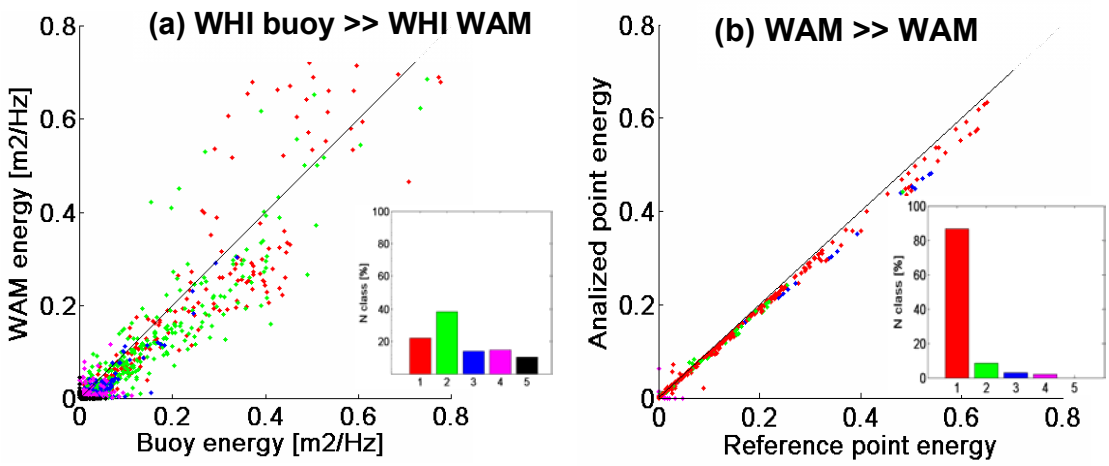


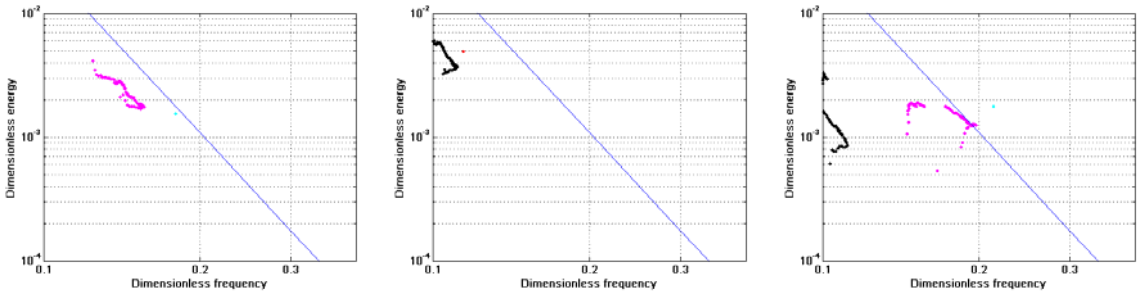
Figure 5 Scatter plots of cross-assigned partitions.

In figure 5, two scatter plots are presented. The different colors correspond to the different goodness of match between components according to the classes' definition given in table 4. The bar plot indicates the percentage of components within certain class for the whole simulation period which corresponds to October 1997. (a) is the comparison of wave components between model and measurements at the buoy location. This plot shows how actually model results compare to buoy measurements in terms of energy frequency and direction. (b) shows a comparison between two model boundary points, what is relevant there is that a similar pattern is expected for each pair of model boundary points; about 90% of the components match under class 1, and there are not components left unmatched (class 5). The presence of classes 2 and 3 gives an indication of the evolution of wave components moving towards shallower waters and the fact that some pairs fall under class 4 can be attributed to

inaccuracies of the partitioning scheme which is kept at marginal levels. This second cross-assignment allows making an identification of the systems along the boundary and thus take into account their spatial persistence.

4. DISCUSION

Besides the cases and considerations given by Lionello et al., 1992, the present implementation is confronted with additional situations. Waves generated on the Belgian shelf are not only subject to time limitations but also to fetch limitations, besides there is the problem of cases with slanting fetches which are particularly complex for modeling, and especially the evolution of wind seas and swells in shallow waters, for which the given approaches and formulations might not be applicable. In figure 6, three examples of different situations like those previously mentioned are illustrated. Figure 7 shows the time series of the measured total wave energy and wind direction at the locations of Westhinder and MP7 for the period of October 1997.



(a) **(b)** **(c)**

Figure 6 Different states of the wave spectrum

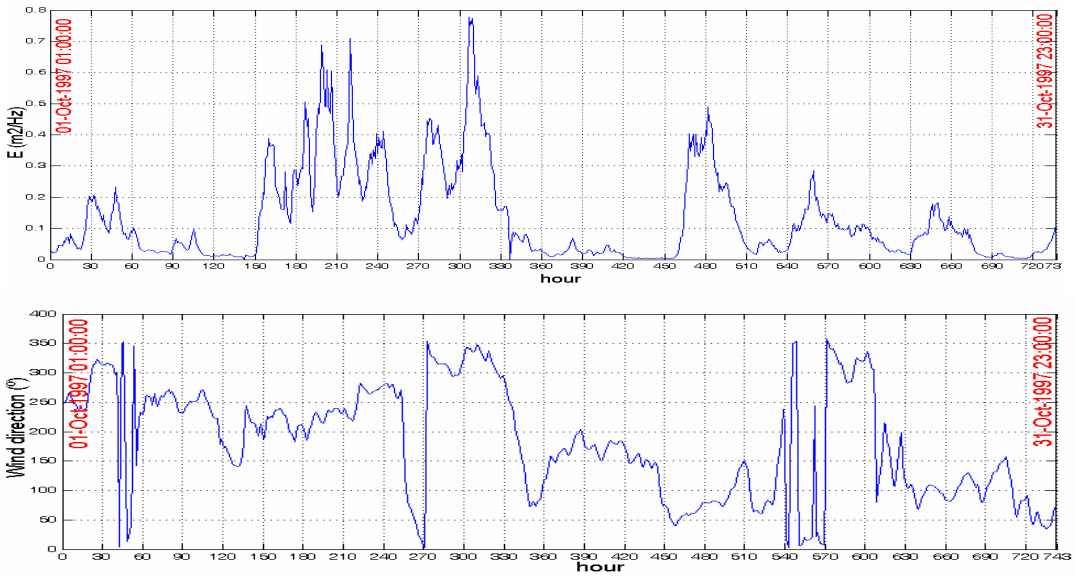


Figure 7 Time series of total wave energy and wind direction for the simulation period (October 1997).

Figure 6 shows three different instant states for which dimensionless energy has been plotted against dimensionless peak frequency for all boundary points and all components at that instant. Model components are indicated in magenta if they are considered wind sea or in black if they are swells; buoy components are indicated in cyan for wind sea and in red for swell. (a) corresponds to the hour state 308 (refer to figure 7), which corresponds to wind sea growing with relatively constant winds coming from north; from the distribution of points on the logarithmic plot there is a clear indication that they follow a power relationship and thus the update could be done accordingly. The blue solid line corresponds to the power relation of Knowles, 1982 for finite water-depth. (b) corresponds to instant 322 which is the decay period of the same system, and (c) shows the state at hour 339 where two systems coexist due to the presence of a moderated wind that change direction relatively fast.

5. CONCLUSIONS

The implementation of intermediate smoothing steps in the partitioning scheme as a method for simplifying and improving the combining of partitions has output satisfactory results avoiding the introduction of parameters. Although the type of filter employed here is arbitrary and other type of filters ought to be study.

The normalized square distance in the wave number space is not a good criterion for cross-assignment. The cross-assignment based on frequency and direction windows gives more consistent results.

The cross-assignment classes defined in this paper are rather arbitrary. This fact does not affect the results of the cross-assignment as such; however, that definition might be crucial for the update of the model spectra, not only for the determination of weighting factors for interpolation, but also for imposing or rejecting partitions that are poorly correlated.

Wave conditions in the near-shore domain are spatially correlated to a certain extent. That correlation opens the opportunity of using offshore buoy measurements for correcting model calculations by means of assimilation techniques.

That spatial correlation is determined mainly by the different meteorological conditions and the consideration of different situations is mandatory for the proper assessment of the wave field correction.

6. FURTHER WORK

This paper makes part of an ongoing research and therefore only preliminary results have been presented. The next important step for the continuation of this study is the update of the boundary model spectrum as such. For that purpose, the different situations explained here are going to be considered.

Besides, weighting factors for the different situations and locations have to be established in order to extrapolate the buoy information without disturbing the physical and numerical constrains of the model and in order to get a significant impact from the analysis.

The analyzed wave field conditions have to be evaluated by means of long term simulations and standard statistical procedures. A significant and positive impact of the analysis will conclude in the implementation of the method in the wave climate calculations.

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