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About the Use of 3rd-Generation Wave Prediction Models for Estimating the Performance of Wave Energy Converters in Coastal Regions

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Abstract—This paper addresses the common uncertainties introduced into the long-term performance estimation of wave energy converters in coastal regions by using 3rd-generation model wave data as input of the simulator. Indeed, the variability observed in hindcast results induces variability in the energy converted by devices, with implications on the long-term power figures. A comparison with estimates based on three different wave model data sources (produced from the WAM, Wave Watch III and SWAN wind-wave models) and buoy measurement data in the nearshore region of the French marine energy test site SEM-REV is made. The paper raises the fact that, in general, a non-negligible error is obtained – even when the wind-wave model has been appropriately designed to the local wave physics – with respect to real converted power values, which in turn results in significantly biased long-term averaged power numbers.

Keywords—Wave modelling; Wave dissipation; Nearshore effects; Wave Energy Converters; Performance assessment.

I. INTRODUCTION

Wave energy development requires figuring out the expectable production of wave energy converters (WECs) at some location of interest – like test facilities or pilot zones. In order to estimate the performance of such devices wave data are required at long term as an input for simulation codes. Wave models are commonly used as a reliable and cost-effective alternative to the deployment of measurement instruments or the purchase of field data, which both might turn out to be far too expensive in relation to pre- and feasibility studies budgets. Therefore, the performance of WECs is often assessed based on wave hindcast data such as global reanalysis data bases, regional/coastal runs etc.

The basic data expected from phase-averaged spectral models like 3rd-generation large-scale, deep and finite water depth ones – which solve the spectral wave action balance equation in space, time, frequency and direction – are synthetic wave parameters such as H_s , T_p and θ_p (respectively derived as four times the square-root of the 0th-order moment, period and direction corresponding to the peak of the directional wave spectrum). Operational models implemented

in oceanographic institutes worldwide are calibrated in particular with regard to these parameters.

However, very little attention has been paid until recently to the shape of spectral data in frequency (and direction), which is the primary result of the equations solved by these models. In the recent years, several authors [1,2] have shown that considering the sole triplet $\{H_s, T_p, \theta_p\}$ might be too restrictive to allow a long-term performance assessment of WECs with a reasonable level of accuracy. From given input data (bathymetry; wind forcing fields; spectral boundaries; currents...) indeed, the spectral terms accounting for dissipation effects (white-capping; bottom friction; depth-induced wave breaking...) have a strong influence on the final energy distribution in the predicted spectra, and therefore, the actual yield of a single WEC or a farm installed nearshore.

In this paper, numerical results obtained in the nearshore location of the French wave energy test site (SEM-REV) are presented by considering different – widely used – wave model data, namely from the WAM [3], Wave Watch III [4] and SWAN [5] models – each with its specific wave modelling characteristics (air-sea exchange; depth-induced breaking; non-linear interactions; structured/unstructured grids...). A comparative study is carried out for the different spectral wave outputs collected against local buoy measurements in regard to the long-term production operated by a Wavestar-like WEC (hybrid WEC-OWT concept developed in the frame of the E.U. MARINA Platform project). The performance of the device is estimated by modelling the whole hydro-mechanical conversion chain as a linear filter – without consideration to wave directionality for simplicity. The long-term production of the WEC as estimated by each of these three sources of data is then compared to that obtained from measurements (considered as the reference). The paper aims to observe the differences obtained between model datasets in terms of power performance and comments on the related uncertainties according to the wave modelling adopted.

The paper is outlined as follows. Section II introduces the wave input data sources: three model configurations and *in situ* measurements for the SEM-REV location. Section III

briefly describes the wave energy conversion modelling of the combined Wavestar-like WEC device used for simulation. Section IV presents and discusses the simulation results for the long-term production. Section V finally concludes on the study.

II. DATA SOURCE: WAVE MODELS AND *IN SITU* MEASUREMENTS

Wave models of 3rd-generation are differentiated from previous generations' ones by the fact that the spectral shape is not constrained by any particular empirical law (e.g. JONSWAP or Pierson-Moskowitz in 2nd-generation models [6], which mostly look for the sea state's energy and mean frequency). The (directional) wave spectral density S is found as the solution of the space and time differential equation (called the *wave action balance equation*), as

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (1)$$

where N denotes the wave action quantity defined as $N = S/\sigma \equiv N(t,x,y,\sigma,\theta)$, which is conserved in the presence of currents unlike the wave directional spectral density [7]. The advection terms in the left-hand member of Eq. (1) account for refraction, shoaling and wave-current interactions, while that in the right-hand member denotes spectral source and sink terms. Indeed, the spectral sum S_{tot} may be decomposed into a sum of components, as

$$S_{tot} = S_{in} + S_{nl} + S_{ds,w} + S_{ds,b} + S_{ds,br} \quad (2)$$

where:

- S_{in} is wind energy input (atmospheric forcing);
- S_{nl} are 2nd- and 3rd-order non-linear wave-wave interactions (*triads* and *quadruplets* resp.);
- $S_{ds,w}$ is white-capping energy dissipation;
- $S_{ds,b}$ is energy dissipation by bottom friction;
- $S_{ds,br}$ is energy dissipation by bathymetric wave breaking.

Depending on the modelling of source and sink terms – assuming similar grid, bathymetry and wind energy input, – the spectral solution of Eq. (1) at a given grid point and time might be found differently shaped and scaled. All models require calibration against *in situ* or remote-sensed measurements but, due to the fact that optimal model settings are often based on a few measurements samples (along satellite paths, buoy networks), wave data at some places may require a specific post-calibration – which is not always possible as measurements are not necessarily available or sufficient.

A. *WAM*

The model *WAM* (Cycles 3 and 4) is known as the first 3rd-generation numerical wave hindcast model developed in

Europe by the *WAMDI* group in the late 80s [3]. Wind input and dissipation (white-capping), non-linear wave-wave interactions (quadruplets) and bottom friction were implemented for the first time without any constraint on the spectral shape. This model is routinely run today by ECMWF (Reading, UK) – under continuous technical support of GKSS (Geesthacht, Germany) – to produce global long-term wave reanalysis databases such as ERA-40 or ERA-Interim [8,9] as well as wave forecasts. *WAM* has been used in particular to build wave energy atlases such as the *WERATLAS* [10].

B. *Wave Watch III (WW3)*

The American version of 3rd-generation model is known as *Wave Watch III (WW3)* [4]. Very similar to *WAM*, *WW3* includes alternative formulations for source and sink terms such as dissipation [11] or non-linear wave-wave interactions [12]. Depth-induced wave breaking as formulated in [13] is also included. Like *WAM*, *WW3* requires regular Cartesian gridding (with possible nesting) although unstructured grids may be used in non-public versions of the code (see Subsection D.). *WW3* is currently implemented at the NOAA to produce global wave reanalysis and forecasting. New spectral formulations are regularly tested by co-developers of the code and possibly implemented in next releases [14-17].

C. *SWAN*

Even though refraction, shoaling, bottom friction and wave-current interactions are included in global models such as *WAM* or *WW3*, the basic parameterisation is not *a priori* adapted to nearshore and coastal regions, where the influence of bathymetry on wave trains is dominant. Depth-induced breaking along with the most recent dissipation formulations implemented in *WW3* [15,16] permitted to make results more accurate however. For possibly complex nearshore and coastal regions (irregular coasts, islands, peninsulas, creeks, harbours...) a specific code – with specific numerical scheme – has been developed by TU Delft (*SWAN*) to help focus on coastal and shallow water effects [5,6]. Source and sink terms similar to *WW3* are included in *SWAN* along with 2nd- and 3rd-order non-linear wave-wave interactions (triads + quadruplets), which are introduced to account better for such interactions in finite or shallow water depths. Variations of the mean water level may also be taken into account. Such a model obviously requires a finer resolution for all data fields (bathymetry, wind, boundary conditions...).

As a regional tool, *SWAN* is generally run using boundary conditions outputted by a primary global model (*WAM* or *WW3* for instance).

D. *Model configurations*

The wave model date considered in this work correspond to the location of the French marine energy test site SEM-REV (47.239°N, 2.779°W, Fig. 1). Wave spectral datasets were produced for the year 2010, which are used as spectral input to the hydrodynamic model of Wavestar-like WEC described in next section. Table I lists the characteristics of the three independent wind-wave model configurations used in this work for providing the spectral data.

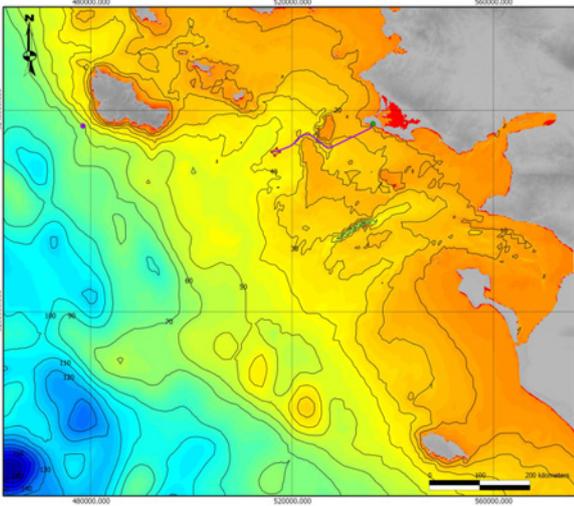


Fig. 1 Geographic area of the SEM-REV marine test facility (South of French Brittany – Atlantic Ocean).

The WAM Cycle 3.3 R1 model was run by the National and Kapodistrian University of Athens (NKUA) on a fine Europe-focussed grid ($0.05^\circ \times 0.05^\circ$) for a 10-year wave re-analysis [18]. Hourly spectra are obtained for a location close to SEM-REV (47.25°N , 2.75°W). This model configuration is denoted by ‘M1’ in the following.

Based on the latest developments of the WW3 source code at Ifremer Brest Centre (France), a modelling chain has been designed and run at ECN based on the latest developments of the WW3 source codes, with the addition of advection schemes on unstructured grids, cf. Ardhuin *et al.* [17]. Hourly spectra are obtained for a location central to the SEM-REV area (47.24°N , 2.79°W). This model configuration is denoted by ‘M2’ in the following.

The SWAN model has been run at ECN using – as boundary conditions – WW3 output spectra on a $0.5^\circ \times 0.5^\circ$ grid produced by the University of La Rochelle (France) [19]. 6-h spectra are obtained for a location central to the SEM-REV area (47.239° , 2.7788°W). This model configuration is denoted by ‘M3’ in the following.

E. In situ measurements

Wave conditions in the SEM-REV test site are continuously monitored thanks to two directional Datawell MkIII buoys located at either side of the zone (East/West). The data are both stored on the memory card on board and sent *via* VHF to the inshore station. The data consist in buoy motions time-series (heave and horizontal motions) sampled at 1.28Hz, from which an estimate of the wave spectrum can be derived e.g. every half-hour or hour. Hourly directional wave spectra are estimated (using FFT and maximum entropy method [24]) and integrated over directions with resolution 0.01Hz ($0.063\text{rad}\cdot\text{s}^{-1}$). The time span for comparisons is year 2010 and spectral data coming from both wave buoys are jointly used in this work (Table II). In particular, the western buoy data cover nearly 8 months in 2010.

TABLE I
CONFIGURATION OF WAVE HINDCAST MODEL DATASETS

	M1	M2	M3
Model	WAM C3.3 R1 [3]	WW3 (non-public version) [4]	WW3 v. 3.14 [4] + SWAN v. 40.85 [5]
Type	Large-scale regional (Europe)	Global/Regional (nesting Northern Bay of Biscay)	Global (WW3) + Regional (nesting of Loire’s estuary zone in SWAN, Fig. 1)
Reference	Cradden <i>et al.</i> [18] (10-year re-analysis)	Internal ECN	Dodet <i>et al.</i> [19] and Le Crom <i>et al.</i> [20]
Forcing & dissipation modelling	Bidlot and Janssen [14]	Ardhuin <i>et al.</i> [16]	Ardhuin <i>et al.</i> [15] + Janssen [21]
Mesh grid (resolution)	Structured ($0.05^\circ \times 0.05^\circ$)	Structured (0.5° and 2min) & unstructured (up to 100m)	Structured ($500\text{m} \times 500\text{m}$ nesting)
Output time step	1h	1h	6h
Wind input	SKIRON atmospheric model (3h, $0.05^\circ \times 0.05^\circ$) + CIRCE re-analysis	ERA-Interim (6h, $0.75^\circ \times 0.75^\circ$)	NCEP/NCAR (6h, $0.5^\circ \times 0.5^\circ$) + ERA-Interim (6h, $0.75^\circ \times 0.75^\circ$)
Boundary conditions	-	WW3 North Atlantic model + Northern Bay of Biscay	WW3 global [19] ($0.5^\circ \times 0.5^\circ$)
Bathymetry	ETOPO	ETOPO/ GEBCO [22] + SHOM [23]	SHOM [23]
Frequency range	0.055Hz to 0.5417Hz	0.0373Hz to 0.7160Hz	0.0412Hz to 0.4060 Hz

TABLE II
BUOY MEASUREMENTS IN SEM-REV (2010)

Characteristics	E-buoy	W-buoy
Location	$47^\circ 14.34'\text{N}$; $2^\circ 46.27'\text{W}$	$47^\circ 14.34'\text{N}$; $2^\circ 47.19'\text{W}$
Available data	08/08/2010 to 31/12/2010	11/01/2010 to 12/05/2010 and 29/06/2010 to 06/10/2010
Mean depth	35m	35m

III. WEC MODELLING AND SIMULATION

The WEC chosen to carry out the analysis (depicted in Fig. 2 below) is inspired from the Wavestar concept [25] and was numerically modelled within the frame of the European project *MARINA Platform*. This project brings together expertise from offshore wind and ocean energy industries to develop floating platforms that combine offshore wind turbines (OWTs) and WECs. Additional information is available on the project website [26]. Initially, some segregated concepts were proposed to harness the wave energy available in fixed offshore wind parks as sharing the space and installation expenditures would be expected to reduce the project costs. These shallow water concepts are well adapted to the wave model comparison at the SEM-REV location.

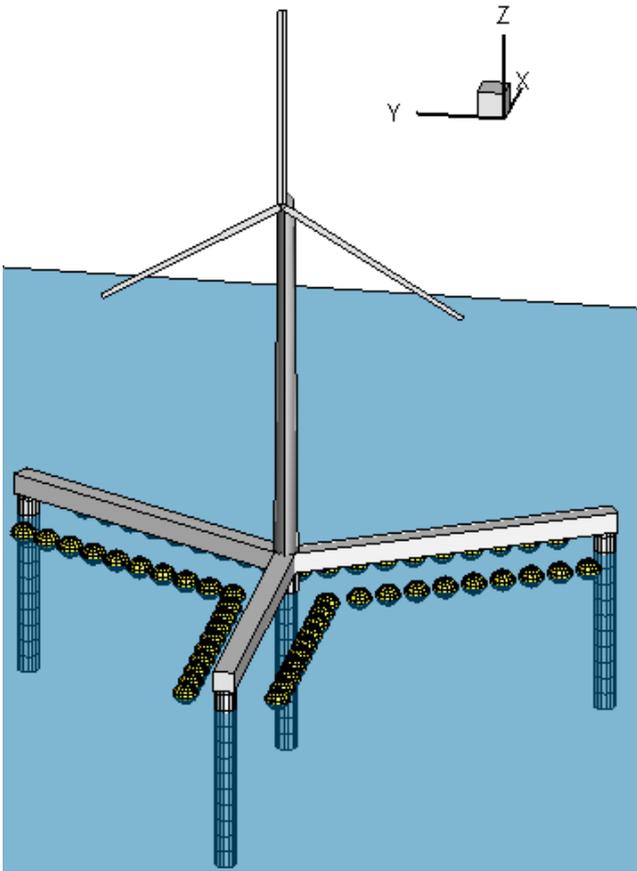


Fig.2 Design of the hybrid Wavestar WEC-OWT.

A. Wave Energy Device

The WEC considered consists of 57 point absorbers distributed on three main beams. These beams are to be deployed around fixed mono-pile wind turbines in offshore parks. The main dimensions of the device are detailed in Table III.

TABLE III
MAIN DIMENSIONS OF THE HYBRID WEC-OWT

Characteristics	Units	Value
<i>Platform</i>		
Beam Length	m	80
Column diameter	m	5.0
Displacement	t	3140
Water Depth	m	40
<i>Wave Energy Converters</i>		
Number of buoys	-	57
Radius	m	3.0
Draft	m ²	2.56
Mass	t	61
<i>Wind Turbine</i>		
Rotor Diameter	m	126
Nacelle Height	m	100

B. Numerical Model

A numerical frequency domain Wave-to-Wire (W2W) model was built to assess the wave power produced by the WECs.

This W2W code is based on linear potential theory for the fluid structure interactions. The hydrodynamic coefficients are calculated with the in-house BEM software Aquaplan [27] and the main dynamic assumptions were described in [28]. The waves are supposed to be mono-directional, and the loads are linearized under the small amplitude approximation. It is assumed, here, that wave directionality has a negligible effect onto the response of the whole structure – as for a point absorber. In reality, directionality is expected to be influential on the device at short term; however, for the purpose of this study this aspect is not deemed crucial and waves are considered as unidirectional for simplicity.

Each buoy is modelled independently and hydrodynamic interactions are taken into account. In order to reduce the total number of degrees of freedom, the buoys are constrained to heave motion only. The hydraulic PTO is modelled as linear damper.

Each buoy is represented by a partly submerged sphere, which is connected to the supporting beam by a rigid arm and a hinge. The wave power is extracted through the angular motion of the arm thanks to a hydraulic Power Take-Off (PTO) system positioned above water, at the hinge. Wind loads are not modelled here (uncoupled aero-hydro approach).

The implementation of such a fully linear model in the frequency domain allows fast calculations. With non-linear time domain models, the CPU time required to assess the power production for different wave models – and over a full year – would be significantly higher. The mechanical power absorption of the whole device is then represented in the frequency domain by a single power transfer function $P(\omega)$ in

$\text{MW}\cdot\text{m}^{-2}$ (ω denotes circular frequency in $\text{rad}\cdot\text{s}^{-1}$). The integration of the product of transfer function and the wave spectrum $S(\omega)$ yields the mean power for each sea state as [1]

$$\bar{P} = \int P(\omega)S(\omega)d\omega \quad (3)$$

IV. LONG-TERM PRODUCTION RESULTS AND DISCUSSION

The performance of the WEC has been assessed precisely based on five different sources of spectral densities, namely: the western buoy (taken as the reference), the eastern buoy and datasets M1, M2 and M3. The same frequency discretization has been adopted for each ($\Delta\omega = 0.0161 \text{ rad}\cdot\text{s}^{-1}$) – wave spectra are re-sampled accordingly – and an estimate of the mean converted power in MW is calculated at each time step (1h for all but M3). Excerpts of the resulting time-series are plotted in Figures 3(a-c). Then, each time-series is compared to the reference results (western buoy) by means of statistical indicators such as the normalised root mean square error (NRMSE) defined as

$$\text{NRMSE}(X,Y) = \sqrt{\frac{\sum_i (X_i - Y_i)^2}{\sum_i X_i^2}} \quad (4)$$

Pearson's correlation coefficient (Corr)

$$\text{Corr}(X,Y) = \frac{E[X \cdot Y] - E[X] \cdot E[Y]}{\sigma[X] \cdot \sigma[Y]} \quad (5)$$

and scatter index (SCI)

$$\text{SCI}(X,Y) = \frac{\sqrt{E[(X-Y)^2]}}{E[X]} = \sqrt{\frac{\sum_i (X_i - Y_i)^2}{N}} \quad (6)$$

where N is the sample's size, $E[\cdot]$ denotes arithmetic mean and $\sigma[\cdot]$ the (biased) standard deviation (i.e. normalised by N). The value of each parameter is given in Table IV. As M3 spectral data correspond to 6h outputs, cross-statistics for 6h-output M1 and M2 have been produced as well, which are given in brackets in Table IV. The results show that the time step has no influence on the statistics corresponding to M1 and M2 however.

It is firstly observed that the power estimation based on spectral densities estimated by two close wave measurement buoys (distant from each other by about one kilometre) during about two months varies by nearly 10% NRMSE. This means that an error of the same amount at least on the power estimate is expected as inherent to the variability of the wave field within the SEM-REV area. In addition to statistical variability, wave non-linearity as well as specific features of the bathymetric and current conditions upstream may also account for the on-site heterogeneity (see Fig. 1).

Secondly, large differences are found for all three model data as compared to the reference buoys' ones. The lowest NRMSE is found for M2 input (~30%, SCI ~ 61%). The largest error is found for M1 (~108%, SCI ~222%) and M3 input data yield intermediate estimates (NRMSE ~ 63%, SCI ~ 129%). In the longer term, the relative bias on the mean power averaged over two months found by comparing the eastern buoy to the western one is inferior to 2%, which indicates that the site may be considered as homogeneous for this purpose. However, M2, M3 and M1 data yield relative biases of about +12%, +38% and +57% respectively, which might induce large errors in commercial pre-studies.

The configuration and settings of the input model data are therefore very influential on the long-term power estimate. It is seen here (Fig. 3) that M1 power results are much higher than M2 and M3 in energetic sea states, which is greatly due to the too weak dissipation of energy as waves approach the coasts. In the WAM model, indeed, depth-induced wave breaking is not implemented and air-sea exchange formulations are different, as emphasized in Section II. Power estimates for M2 and M3 input data (which are 'filtered' by SWAN for the latter) are found much closer to the reference curve, indeed. M1 data could be seen as 'raw' input data, which would further require calibration or nested gridding next to the shore – including wave breaking effects. That is why the present results obtained for M1 in a nearshore location like SEM-REV are not too surprising. M2 data have been provided by specialists in ocean and coastal wave models (Ifremer, ECN), whose last improvements are not available to the public yet. M2 data, therefore, may be considered as 'highly refined' and well fitted to the location, which explains that a low NRMSE is found. Nevertheless, the bias on the long-term power estimate is still not negligible (+12%). Data of M3's type are much more commonly produced by consultants and engineers in preliminary studies for wave energy project design. Although the power estimates are found a little more accurate than with M1 data, there might still be a bias in the long-term power expectation – approaching +40% here.

V. CONCLUSIONS

Using global/regional 3rd-generation wind-wave models for assessing the performance of wave energy devices – through the consideration of the output wave spectra – in nearshore regions is often necessary but requires being very cautious. This study has shown indeed, for the particular location of SEM-REV in 2010 and Wavestar-like WEC, that a significant over-estimation was generally obtained for the long-term power estimate, with NRMSE against measurements-derived values ranging from 30% to more than 100% according to three different models and configuration settings (WAM 'M1', WW3 'M2' and SWAN 'M3', the lowest error being obtained here for the non-public, specific version of the WW3 model, 'M2'). As a consequence, the long-term averaged power value resulted as biased by +12% to +60%.

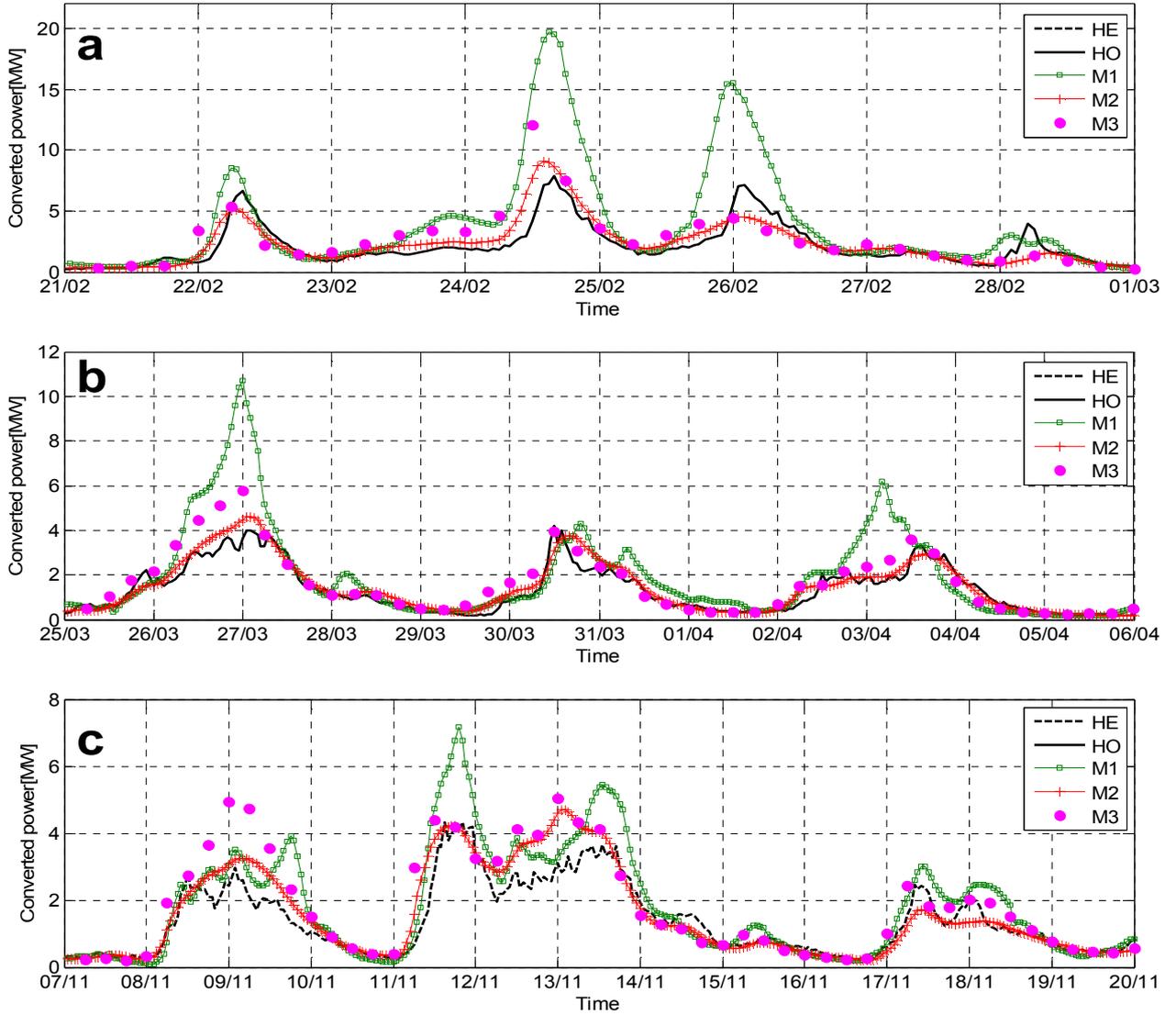


Fig.3 Excerpts of long-term converted power estimation [MW] based on M1, M2 and M3 spectra and corresponding estimates from western ('HO') and eastern ('HE') buoy in SEM-REV: 21/02/2010 to 01/03/2010 (a), 26/03/2010 to 06/04/2010 (b), and 07/11/2010 to 20/11/2010 (c).

TABLE IV
COMPARISON STATISTICS OF EASTERN BUOY AND MODELS M1, M2 AND M3 FOR CONVERTED POWER ESTIMATION AGAINST WESTERN BUOY
(NUMBERS IN BRACKETS DENOTE 6H-STEP DATA)

Statistics vs. W-Buoy	E-Buoy	M1	M2	M3
NRMSE[%]	9.0 (8.2)	107.7 (109.3)	29.6 (30.6)	-(62.8)
Corr.[-]	0.994 (0.996)	0.889 (0.886)	0.954 (0.951)	-(0.877)
SCI[%]	15.3 (13.9)	221.2 (223.8)	60.9 (62.3)	-(128.6)
Mean Power rel. bias[%]	+1.7 (+1.9)	+56.7 (+57.2)	+11.7 (+11.6)	-(+38.2)
N	1439 (239)	5307 (884)	5307 (884)	-(884)

It is evident that a global oceanic model like WAM ('M1') should not be used directly for such purposes and should rather be used to constrain the boundaries of a finite/shallow water propagation model like SWAN. However, even though resorting to a nearshore wave model focused on coastal zones helps reduce the error on the power estimate, non-negligible errors are still expected (~60% NRMSE and ~+40% relative bias on long-term averaged power for 'M3').

The study has also incidentally demonstrated (based on two months of field data in 2010) that an 'incompressible' error of about 10% was found for the power estimates calculated from two closely deployed wave measurement buoys (~1 kilometer). If in the long term, the relative bias of the averaged power estimate is found to be small (< 2%), this indicates, however, that non-negligible discrepancies may be punctually found from measurements carried out within the same area – most probably due to statistical variability, non-linearity and possible inhomogeneity of the wave process locally.

Dedicating time to produce the best model outputs – regarding spectral shape and overall energy in particular – to field observations is recommended whenever possible anyway in order to reduce uncertainties. To this end, wave energy dissipation effects in finite water depths (white-capping, depth-induced wave breaking...) should be carefully identified and formulated for the regions of interest beforehand. Accurately assessing the local wave energy resource (in spectral shape and energy) is capital, indeed, for the further assessment of WECs.

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