Wave energy resource off the French coasts: the ANEMOC database applied to the energy yield evaluation of Wave Energy Converters

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Abstract

A numerical wave database called ANEMOC has been built by EDF R&D LNHE by hindcasting wave conditions over a period of 23 years and 8 months, between 1979 and 2002. The simulations of wave conditions are carried out with the third-generation spectral wave modelling software TOMAWAC and are driven by wind fields from the ERA-40 meteorological reanalysis produced by the European Centre for Medium-range Weather Forecast. Two nested models, an oceanic one and a coastal one, which zooms on the French coasts of Atlantic Ocean, English Channel and North Sea, have been implemented. The results have been validated with buoy data over a period of two years, and can be used to determine medium wave conditions as well as statistically extrapolated extreme wave heights.

After a description of the main characteristics of the database, the paper focuses on the application of such a database for evaluating the wave energy resource and the wave energy yield of Wave Energy Converter (WEC) technologies in Europe, and in particular off the French coasts.

Keywords: Wave atlas, wave energy resource, WEC energy yield, third generation spectral wave model.

Nomenclature

c_g	=	group velocity (ms^{-1})
F	=	directional variance spectrum ($m^2Hz^{-1}rad^{-1}$)
f	=	frequency (Hz)
h	=	water depth (m)
H	=	wave height (m)
H_{m0}	=	spectral significant wave height (m)
P_W	=	wave energy flux (Wm^{-1})
T	=	wave period (s)
T_e	=	mean energetic period (s)
T_m	=	mean wave period (s)
θ_m	=	mean wave direction (rad)
ρ	=	density of seawater ($kg\ m^{-3}$)

1 Introduction

Wave climate characterization is a crucial aspect for evaluating the energy potential of a Wave Energy Converter (WEC) at a given location and for adapting the machine design to the local wave climate in order to improve its energy yield and/or to reduce the risk of failure in stormy conditions.

Beside field and remote-sensing measurements, recently implemented numerical wave atlases allow such a sea state characterization, enabling to map the wave energy potential, to carry out a preliminary evaluation of the energy yield of WECs and to identify and compare the most favourable sites for their deployment.

Furthermore, a validated wave atlas based on hindcast of wave conditions over a long enough period enables to carry out statistical analysis of extreme wave conditions. The estimation of extreme values of significant wave height and of associated wave period for return periods of up to 50 or 100 years is a crucial aspect to take into account to develop a WEC design able to withstand extreme storm conditions.

Several numerical sea-states databases have been recently built either at global or at regional scale. For example the ERA-40 data set produced by the ECMWF [www.ecmwf.int], and the derived KNMI/ERA-40 wave atlas [1] are provided on a 1.5° by 1.5° latitude-longitude grid, covering the whole Earth. Several hindcasts were also performed within the European Union funded HIPOCAS project [2], providing more detailed results in the continental and coastal European seas, including high-resolution data sets over a selection of European areas, such as the North Sea, the Irish Sea, the West Iberian coasts, the Mediterranean Sea, the Black Sea, the Baltic Sea as well as the Azores and Canary Islands. Regarding the areas off the West French coasts, detailed numerical sea-states data are available from the ANEMOC database coastal model, presented in this paper. This database includes in particular the coastal areas off the French Atlantic coasts, which present a significant wave energy potential. Several locations have been identified there as potential sites for WECs deployment. One of those areas, Le Croisic (Pays de la Loire) has been recently chosen to realize SEMREV, the first French wave energy test centre [3].

2 The ANEMOC database

The ANEMOC database is based on hindcast simulations performed with the third generation spectral wave code TOMAWAC [4] developed at EDF R&D National Hydraulics and Environment Laboratory (LNHE). TOMAWAC solves the wave action density balance equation (e.g. Bretherton and Garret [5], Komen et al. [6]) and models the evolution of the directional wave spectrum in space and time, under unsteady wind forcing. It takes into account the energy input from the wind, nonlinear wave-wave interactions, and dissipation processes due to white-capping, bottom friction and depth-induced breaking in shallow water areas.

The spatial grids used by TOMAWAC are unstructured (triangular elements), allowing to refine the mesh in areas of complex bathymetry and irregular shoreline, e.g. in case of nearshore and coastal applications. The TOMAWAC code has already been validated for the hindcast of several real storms [4], [7].

Two nested numerical models have been set up at different scales, and calibrated: the oceanic and the coastal model. In both models the wave spectrum grid considers 21 frequencies, varying between 0.04 Hz and 0.4 Hz and defined on a logarithmic scale ($\Delta f/f=0.122$), and 36 directions (constant angular resolution of 10 deg.). The output results are stored with a hourly time-step. Both models are run with steady-state water levels (corresponding to the mean tidal level) and without considering tidal current effects. The TOMAWAC code, however, can take into account unsteady currents and water levels.

Part of the results of wave climate analysis can be found on the ANEMOC website, administrated by the CETMEF, at:

http://anemoc.cetmef.equipement.gouv.fr/anemoc/

ANEMOC is a joint collaboration between EDF R&D LNHE and CETMEF (French Ministry in charge of Coastal and River Works).

Oceanic model

The coarser (OCEANIC) model covers the Northern part of the Atlantic Ocean (30°N to 70°N in latitude and 50°W to 10°E in longitude) and has a grid of variable mesh size varying from about 1 degree offshore down to 20 km along the French coastline (see Fig. 1). No wave spectra are imposed at the boundaries of this model: it is assumed that all the wave energy is generated inside the domain considered. Finite depth effects are modelled in the simulations (refraction, shoaling, bottom friction), but not depth-induced breaking.

Coastal model

The finer (COASTAL) model) covers the European continental shelf sea and the English Channel (see Fig. 2). The mesh reaches a resolution of about 2 to 3 km in the nearshore French domain and along the French coasts. Hourly directional wave spectra provided by the OCEANIC model are imposed as boundary conditions. Shallow water processes (including breaking) are considered in the model.

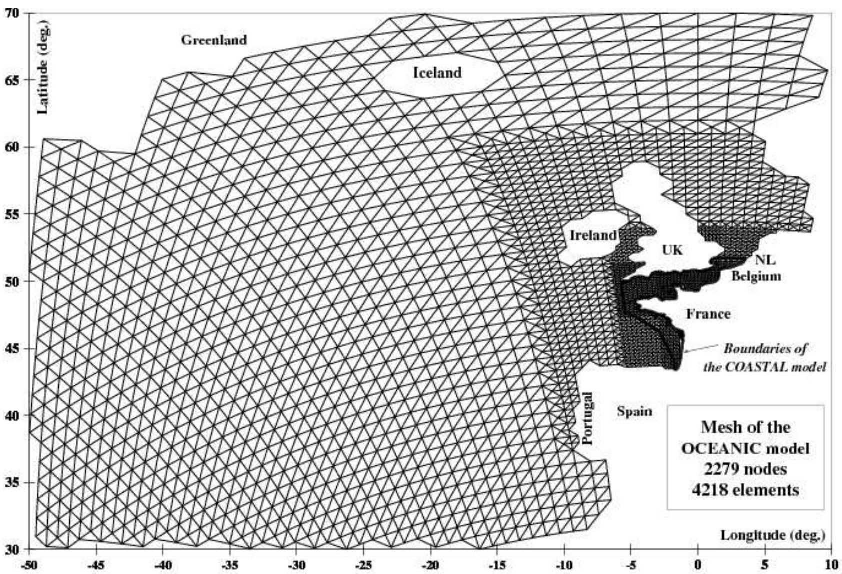

Figure 1: Spatial mesh of the OCEANIC model of the ANEMOC database.

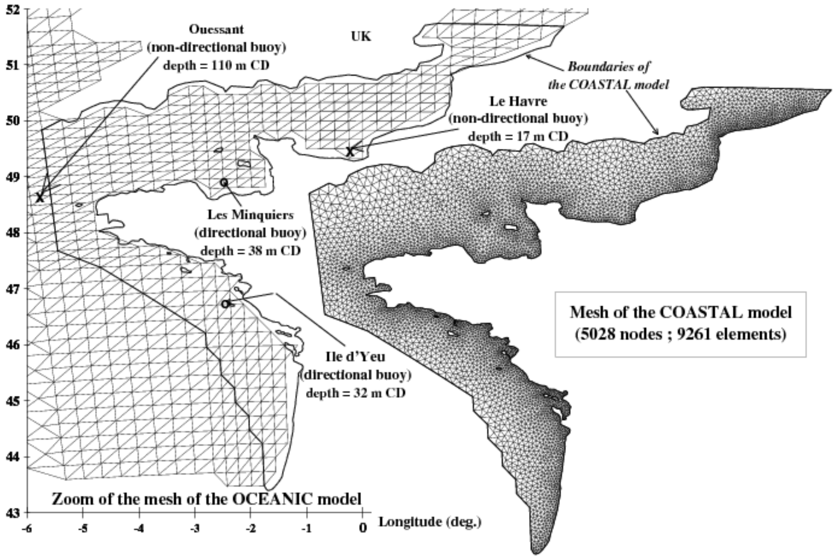

Figure 2: Mesh of the coastal model (right panel) of the ANEMOC database compared with the mesh of the oceanic model zoomed near the French coasts (left panel). The figure shows the locations of four wave buoys used to validate the models.

Wind data

Two meteorological reanalyses (each of them reporting the two components of the 10m wind speed U_{10}) have been taken from two different sources: ERA-40 re-analysis coming from the European Centre for Medium-range Weather Forecast (ECMWF), provided over a rectangular grid of 1.125° x 1.125° and interpolated over a grid of 0.5 x 0.5 degree resolution, and version 2 of NOAA/NCEP reanalysis, provided over a Gaussian-type grid, whose mesh size is about 1.875 degrees. Both wind fields are provided at six-hours intervals. Within the wave model the wind data are linearly interpolated both in space over the irregular computational grid and in time to match the computational time step (15 minutes for the oceanic model and 4 minutes for the coastal one). The influence of the wind data source on wave simulations while building ANEMOC has been examined in [8], and revealed that the results based on ERA-40 winds are slightly better than those obtained with NCEP2 ones. The numerical wave database here illustrated consists of hindcast results of the OCEANIC and COASTAL models driven by ERA-40 winds over the period 01/01/1979 to 31/08/2002 (23 years and 8 months).

Database validation

The numerical results have been compared and validated with buoy measurements from seven wave buoys of the French network CANDHIS operated by CETMEF, over the period 1999-2000. Fig. 2 points out the locations and the characteristics of the four buoys considered the most significant for the

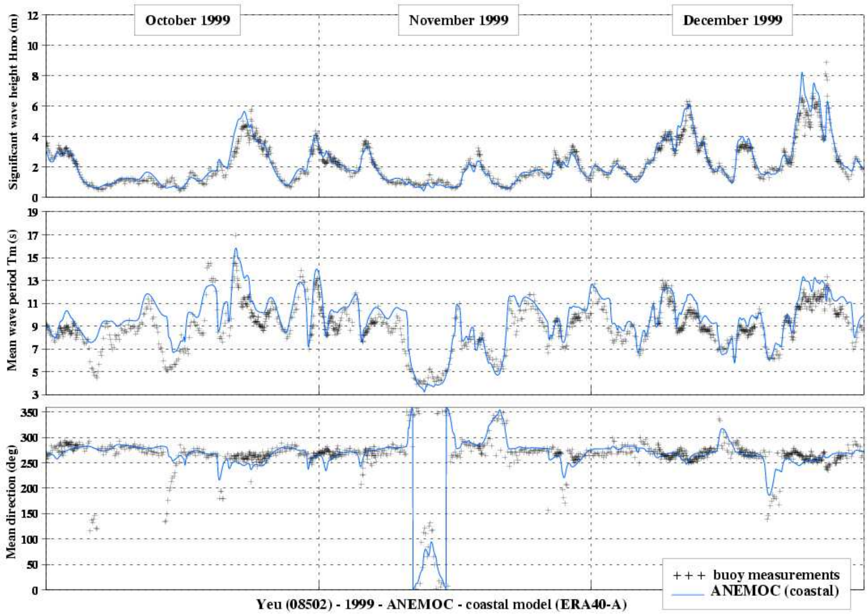

Figure 3: Comparison of model results with buoy data off the Ile d'Yeu for the last quarter of year 1999.

database validation, due to the longer period covered by the measurements.

For the comparison with buoy data the ANEMOC results are linearly interpolated both spatially at the buoy location and temporally at the time of measurement.

Fig. 3 compares computed time series of H_{m0}, T_m and mean incoming wave direction for the last quarter of 1999 with measurements of a buoy off the Ile d'Yeu (buoy code: 08502).

The specific reference to that buoy is motivated by the fact that it is a directional buoy and that the French coasts of the Atlantic Ocean have a favourable potential resource for wave energy applications. The time-series allow a qualitative assessment of the results and show that H_{m0}, T_m and θ_m are fairly well reproduced by the model. Some quantitative measures of the agreement between the measured and computed times series of H_{m0} have also been computed for the same buoy over the years 1999 and 2000: the root mean square error is 0.37 m, and the slope of the regression line is 0.98.

However, temporal profiles of wave parameters do not permit a detailed and quantitative estimation of the model performance and validity. To do so, so-called Q-Q plots are used, which compare measured and computed quantiles (from 1 % to 99 %) of the statistical distribution of reduced sea-state parameters.

Fig. 4 shows the Q-Q plots of the spectral significant wave height (H_{m0}) over the years 1999 and 2000 at the locations of the four buoys above mentioned. The agreement between the simulations and the measurements is fairly good even if a slight trend to overestimate the largest significant wave heights can be noticed. It must be mentioned that the MRU-sensor on-board the Ouessant buoy (upper-left graph) has a consistent tendency to underestimate the highest wave heights.

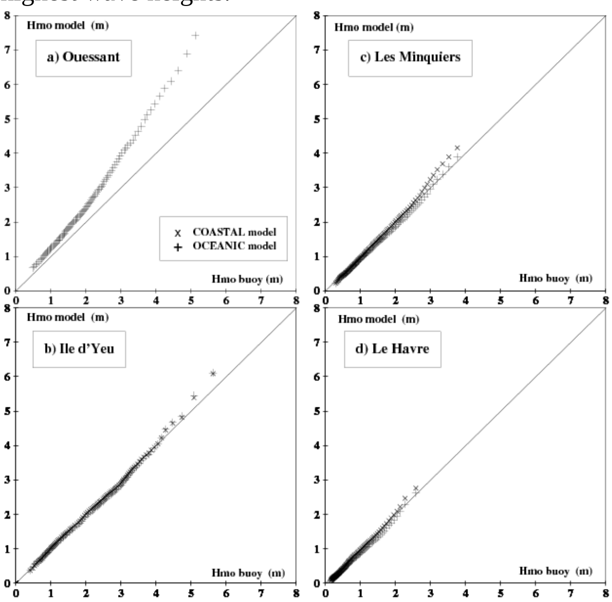

Figure 4: Q-Q plot of H_{m0} for the years 1999-2000 at the 4 wave buoys: a) Ouessant, b) Ile d'Yeu, c) Les Minquiers, d) Le Havre.

Such a deviation was confirmed by CETMEF in 2004 through a comparative campaign involving a Datawell Waverider buoy deployed nearby.

Mean climatology and extreme wave conditions analyses

From the resulting directional wave spectra, sea state reduced spectral parameters (H_{m0}, T_m, T_e, θ_m, P_W, …) are calculated and stored at each node of the two computational grids, every hour over the 23 years and 8 months considered. A database so implemented, consisting of homogeneous data over both the oceanic and coastal domains, and covering such a large time period, represents a significant and robust base to carry out both mean climatology and extreme conditions statistical analyses.

Maps over the two domains as well as occurrence matrices and frequency histograms at each grid node of the models can be obtained for the different sea-state parameters, for both annual and seasonal climatology analysis.

A statistical analysis of extreme wave heights based on the assumption of stationary asymptotic value theory [9] was also performed, using the so-called "Peaks Over Threshold" (POT) method. A detailed description of the methodology used as well as the resulting mapping of extreme wave conditions is described in [10]. The large time period considered in the hindcast simulations allows to estimate extreme wave conditions for return periods of up to 100 years.

A multi-criteria analysis tool

Due to the homogeneity and robustness of the data and to the large time period covered, the ANEMOC database can be used as a tool to carry out multi-criteria analyses for wave energy applications.

The possibility to carry out both mean climatology and extreme condition analyses, enable to couple the mapping of a WEC energy yield to the statistical analysis of extreme wave conditions, to realize a "multi-layer" mapping of the wave resource and help identifying the most favourable sites for a possible deployment of a well defined WEC technology.

In a second phase, once a site has been identified, a more accurate wave climate characterisation can be carried out, by e.g. implementing a local TOMAWAC simulation model based on a more refined local bathymetry and using the ANEMOC data as boundary conditions.

3 Wave energy resource in Europe and along the French coasts

The wave power P_W or energy flux per unit of crest length (in Wm^{-1}) of a sea-state described by its directional variance spectrum, is expressed by:

$$P_W = \rho g \int_0^{2\pi} \int_0^{\infty} c_g(f,h) F(f,\theta) df d\theta \qquad (1)$$

where ρ is the density of seawater, g is the gravity, c_g is the group velocity (ms^{-1}), F is the directional variance spectrum ($m^2Hz^{-1}rad^{-1}$), function of frequency f and direction θ.

The wave power P_W, as defined in (1), is an output parameter of TOMAWAC simulations. ANEMOC provides hourly time-series of P_W values over a period of 23 years and 8 months, at each node of the oceanic and coastal grids.

In the deep-water case, $C_g(f, h=\infty) = g/(4\pi f)$ and Eq. (1), reduces to:

$$P_{W2} = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \qquad (2)$$

where the spectral significant wave height H_{m0} and the mean energetic period T_e are computed as:

$$H_{mo} = 4\sqrt{m_0} \qquad T_e = \frac{m_{-1}}{m_0} \qquad (3)$$

from the n^th spectral moments m_n defined as:

$$m_n = \int_0^\infty f^n F(f) df \qquad (4)$$

Eq. (2) is widely used for estimating the wave energy resource. The assumption of deep water, however, could lead to misleading results in finite-depth or shallow water areas. Results based on the formulations (1) and (2) should be therefore compared to evaluate the reliability of the simplified approach. Such a comparison has been carried out for the oceanic model of the ANEMOC database: for each point of the grid the relative difference $(P_{W2} - P_W)/P_W$ has been calculated and is mapped in Fig. 5. The relative difference lies between 0% and +10% over almost all the studied area. Both formulations lead to very close estimations of the spectral wave power in deep ocean, whereas in shallow waters it can be seen that their relative difference increasesthe error due to the simplified formulation (2) is larger.

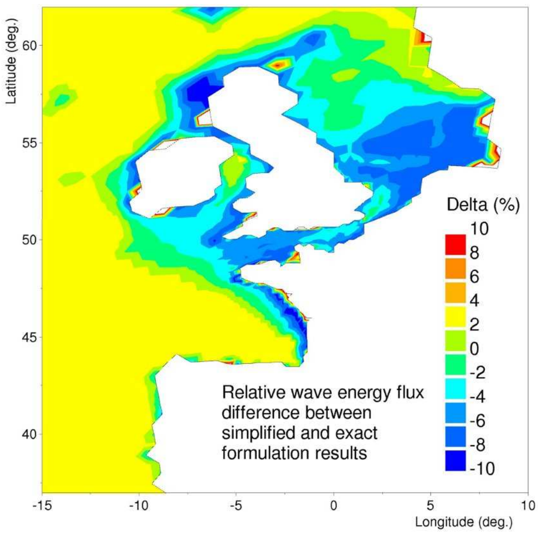

Figure 5: Relative difference $(P_{W2} - P_W)/P_W$ between the wave energy fluxes P_W and P_{W2}, calculated respectively with the correct (1) and the simplified (2) formulations.

The simplified expression, therefore, can be used for a preliminary estimation of the wave energy resource but in case of detailed studies the full formulation (1) should be applied, in particular when considering shallow water areas.

The results which follow in this paper have been obtained applying the correct formulation (1).

The mean annual wave power is computed for the two ANEMOC models over a period of 23 full years (01/01/1979 to 31/12/2001) to avoid introducing a seasonal bias. For each node of the grid the average of the 201624 hourly values included in P_W time-series is calculated, allowing to map both the oceanic and the coastal domains. The maps so obtained represent the maximum resource available of wave energy. They do not depend on any particular choice of WEC technology.

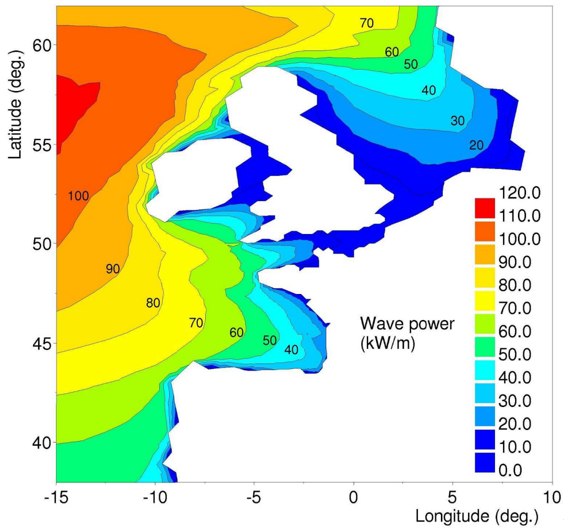

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Figure 6: Mean wave power at European scale (ANEMOC oceanic model).

Fig. 6 shows the mean wave power at European scale. The most energetic regions are those which are directly exposed to large swell generated over the Northern part of Atlantic Ocean, with a wave energy flux varying from about 50 kWm^{-1} off the West Brittany and Cornwell coast, up to about 70 kWm^{-1} on the Scottish North-Western coast and the Irish Western coast. The dominant incoming sector of those energetic sea-states is West. The wave power decrease over the European continental shelf is due to dissipation effects of finite depth processes, such as bottom friction and (in shallow waters) depth-induced breaking. It must be pointed out that the resolution of the coastline and the bathymetry is quite coarse in the oceanic model, and therefore the results obtained in nearshore areas, especially along the coasts of Ireland, United Kingdom and Portugal have to be interpreted with caution.

Specific models at regional or local scale are necessary to refine the wave energy resource assessment in those areas.

The average wave power potential along the French coasts is plotted in Fig. 7. In general, beside the already mentioned West of Brittany, all the

Atlantic French coasts show an interesting wave energy resource. In particular the areas off the Pays de la Loire and off the Aquitaine present a wave energy flux of about 25-30 kWm^{-1} not far from the shore.

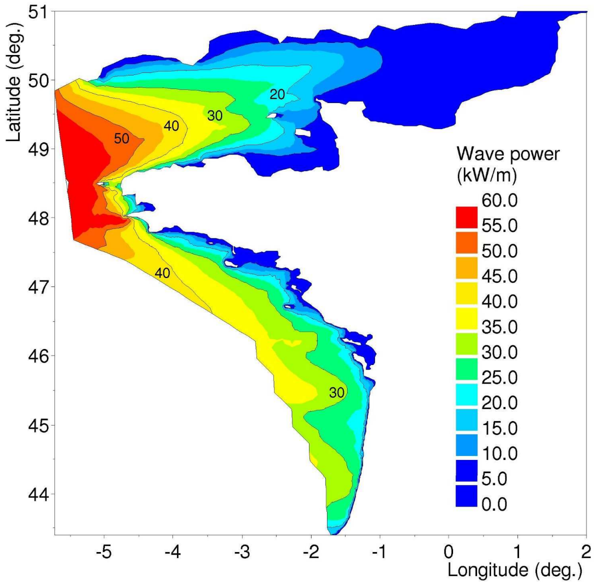

Figure 7: Mean wave power along the French Atlantic coasts (ANEMOC coastal model).

4 WEC energy yield evaluation

The energy yield of a WEC depends on the wave climate at the considered site and on the performance of the device at different wave heights and periods. The data needed for a preliminary estimation of the annual potential of the machine at a given location are the power matrix of the wave energy converter and the wave scatter diagram at that location.

The power matrix describes the performance of the device as function of the wave height H and wave period T: each element (i,j) of the matrix gives the average power generated per wave by the machine for a wave characterized by the couple of values (H_i,T_j). Those power values are obtained either from experimental tests or from numerical simulations.

The scatter diagram describes the sea-state climate at a defined location: each matrix element represents the occurrences of sea-states characterized by a couple of values (H, T). The occurrence is reported as the number of occurrences of sea-states (generally number of hours over the period considered), or as a normalised data (typically integer per mille).

Generally, as suggested by available preliminary protocols [11-12], the wave height and period considered in the power and occurrence matrices are the significant wave height H_{m0} and the mean energetic period T_e.

The energy yield of a WEC at a defined location is obtained by multiplying element by element the power matrix of the machine and the wave occurrence matrix (expressed in number of hours) referring to that location, and by adding together the elements of the matrix so obtained. The final result gives the energy yield of the machine over the duration of the period considered.

Example case: the CETO technology

As example case, the methodology above described is applied to the WEC CETO [13], proprietary technology of Renewable Energy Holding Plc.[1]

The annual energy potential of a machine CETO at the European scale and at the French scale is calculated referring to the ANEMOC database and to the CETO power matrix, as supplied by Carnegie Corporation Ltd, the CETO technology developer, in May 2008 [14].

For each node of both the two models –oceanic one and coastal one- of the ANEMOC database, the occurrence matrix has been calculated as function of the significant wave height H_{m0} and of the mean energetic period T_e. A period of 23 whole years (1979-2001) has been considered for the calculation of the occurrences.

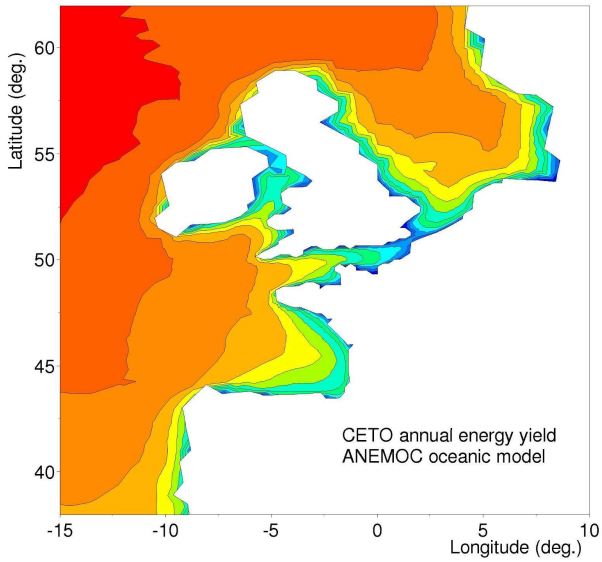

Figure 8: Averaged annual potential energy yield of CETO in Europe, calculated from the CETO power matrix and from the ANEMOC oceanic model.

Fig. 8 shows the annual energy potential of a CETO machine at European scale, calculated referring to the oceanic model of the ANEMOC database.

There is a good correspondence between the CETO energy yield map and the wave resource map plotted in Fig. 6: the energy potential of the machine can be considered roughly proportional to the wave resource, most of all in the deep water areas. A slight discrepancy between the CETO potential and the wave resource map can be observed in the shallower water areas and in the zones not directly exposed to

[1] At the paper submission date, the CETO technical data and energy yield analyses are still confidential. The detailed results could be presented during the EWTEC 2009 Conference.

the waves coming from the Atlantic Ocean. In those areas the wave climate is less rough (lower significant wave heights) and the energy yield of the machine is more affected by the performance of the machine at lower waves, i.e. there is a major influence of the CETO power matrix.

The same considerations are valid when comparing Fig. 7, plotting the wave resource along the French coasts, and Fig. 9, which shows the annual energy potential of a CETO machine off the French coasts referring to the coastal model of the ANEMOC database.

The same procedure for evaluating the energy yield has been used to characterize the monthly potential energy production of CETO. The hourly results of the database have been classified depending on the month they refer: twelve scatter diagrams have been calculated, each of them representing the sea-states occurrences for each month over a 23-years period.

Fig. 10 shows the maps of the averaged daily energy yield along the French coasts calculated for each month. It is evident that the energy potential is higher during the winter period, due to rougher sea states.

Such a variation is illustrated in Fig. 11, in which the relative percent difference between the mean monthly power and the mean annual power (see Fig. 8) is mapped for each month. The mean monthly power can vary over the year from over 1.3 times (winter period) to less than 0.7 times (summer period) the mean annual power in potential areas of interest for wave energy application such as Le Croisic.

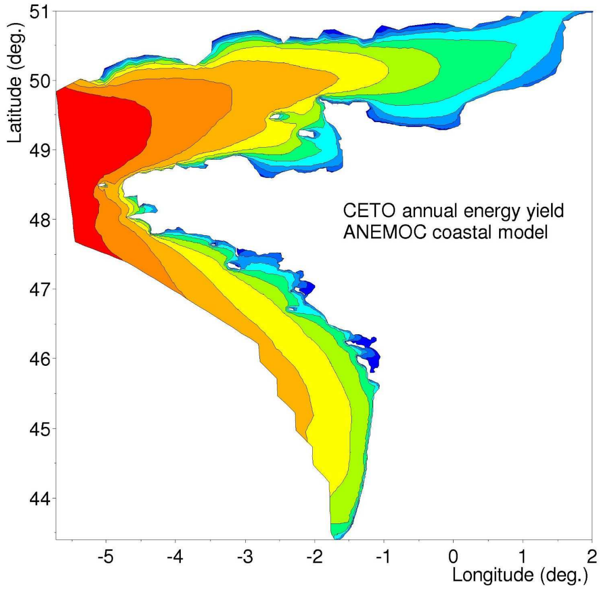

Figure 9: Averaged annual potential energy yield of CETO off the French coasts, calculated from the CETO power matrix and from the ANEMOC coastal model.

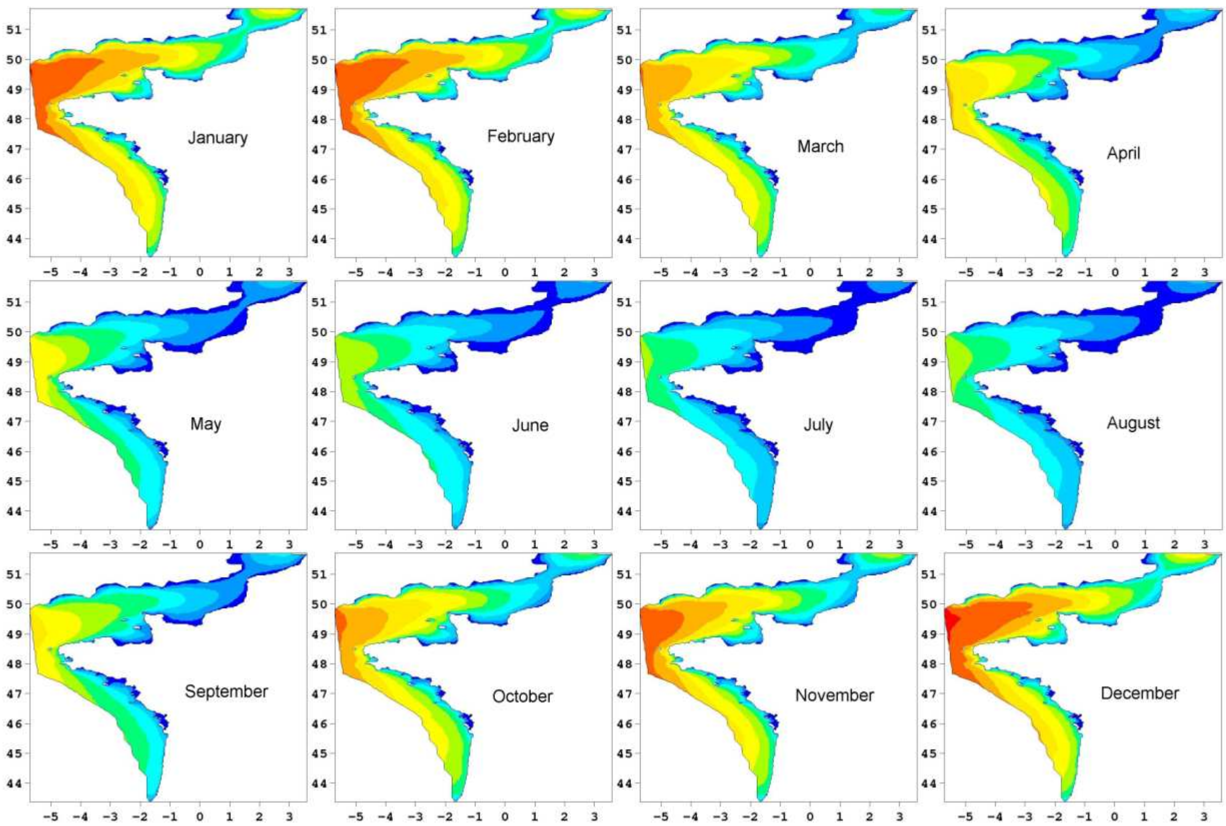

Figure 10: Monthly potential energy yield of CETO off the French coast calculated from the CETO power matrix and from the ANEMOC coastal model.

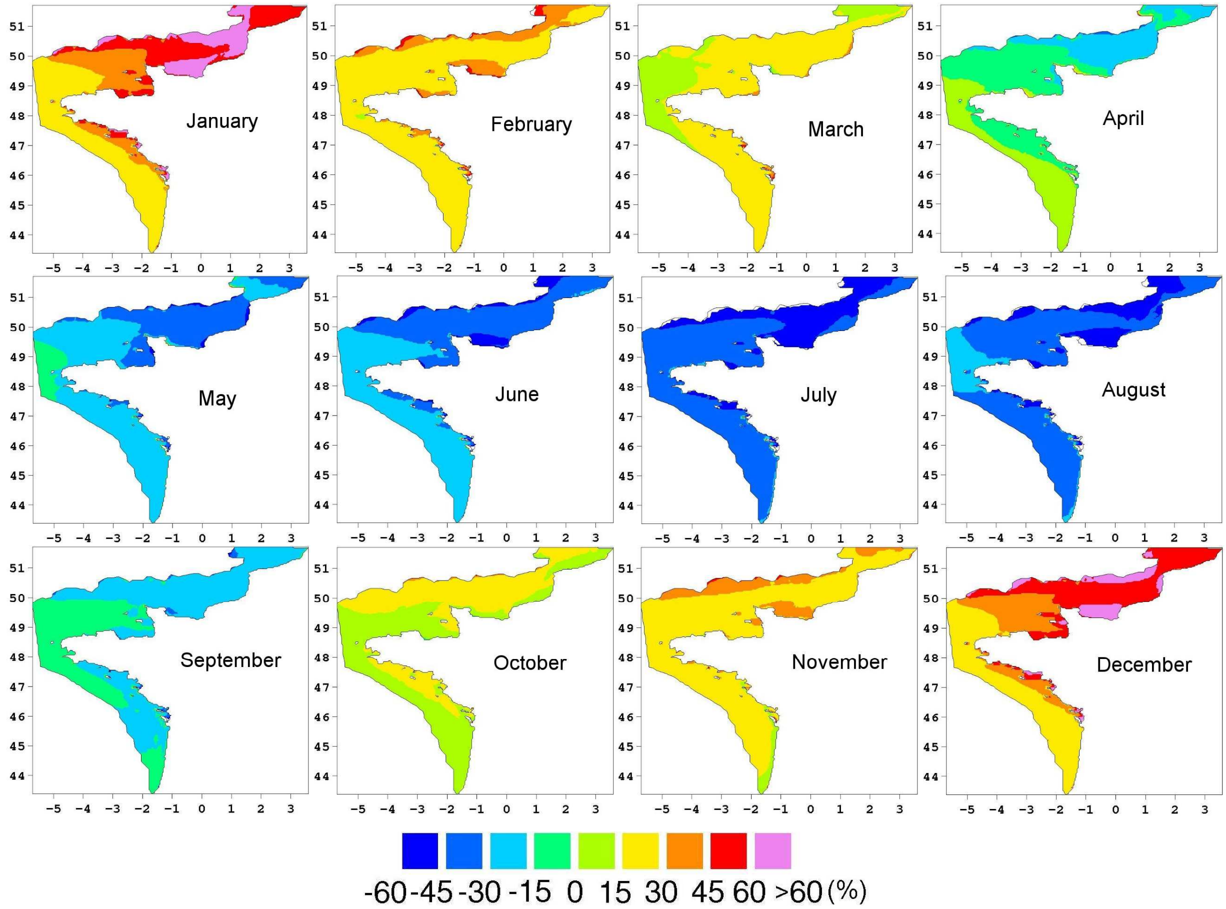

Figure 11: Percent differences between the CETO mean monthly power output and the mean annual power output.

This is clearly pointed out in Fig. 12, which represents the normalised yearly variation of the monthly-averaged daily energy yield for a site located off the Ile d'Yeu (Pays de la Loire): the energy generated in December is twice the energy generated in July.

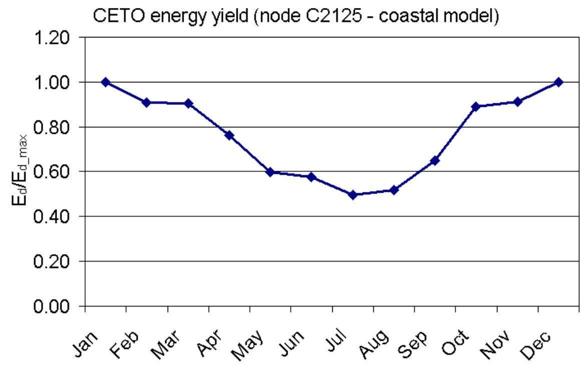

Figure 12: Normalised mean monthly variation of the energy yield of one CETO machine off the Ile d'Yeu.

Present limits of the methodology and further developments

As already pointed out, the methodology presented above is a useful tool for a preliminary mapping of the energy yield of a WEC off the West French coasts.

Such a technique, however, is based on the following simplifying assumptions, which must be overcome in order to characterize more precisely the energy potential of a WEC over those areas:

- in case the WEC power matrix refers to monochromatic and unidirectional waves additional research and tests are needed to improve the methodology for extending such a matrix to irregular and directional sea-states;
- a single machine is considered: the potential interactions between several machines and waves within an array are not taken into account, nor is the effect of an array of machines on the local wave climate;
- tidal effects (ambient currents and water depth variations) have not been considered yet ;

Some of those issues can be addressed via numerical simulation of machine-scale models, or via (scaled) experimental tests, e.g. the evaluation of the machine performance in real sea-states (i.e. in case of irregular waves) or as function of the water depth. However, to represent those effects at a regional scale and to take into account in the energy yield evaluation the other phenomena mentioned above, further work must be carried out both on the TOMAWAC model and on the ANEMOC database. In particular the following two main targets have been identified:

- Including in the TOMAWAC model a local damping term that would represent the real effect of an array of machines on the local sea-state. That means developing a methodology to transfer those WEC effects from a machine-scale model to a regional scale model based on the spectral software TOMAWAC.

- Building an improved version of ANEMOC sea-state database which accounts for current and water depth effects due to the tides, and based on detailed bathymetry and meso-scale wind fields, to improve the accuracy of the wave climate description.

5 Conclusions and further steps

A sea-state database ANEMOC has been implemented via hindcast numerical simulations based on the third generation spectral wave model TOMAWAC. Two nested models, an oceanic one and a coastal one, which zooms over the French coasts, have been implemented. The database covers a period of over 23 years and has been validated with buoy measurements, so that homogeneous and long term time series sea-state parameters are available along the French coasts of Atlantic Ocean, English Channel and North Sea.

The database represents a useful tool for wave energy applications such as preliminary wave energy resource and WECs energy yield mapping, and multi-criteria analysis for identifying the most favourable sites for possible WEC deployments.

The mapping of the theoretical wave resource at European scale and in particular along the French coasts is presented in the paper. The methodology to evaluate the potential annual and monthly energy yield of a WEC technology is also described. As example case, the database has been used to evaluate the energy yield of a WEC based on the CETO technology.

Further work on the ANEMOC database and on the TOMAWAC model is required to overcome some simplifying hypotheses and take into account tidal effects (current and water level variation) and interactions between machines (interference effects between machines and effect of an array of WECs on the nearshore wave climate).

Acknowledgements

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