A NEARSHORE WAVE ATLAS ALONG THE COASTS OF FRANCE BASED ON THE NUMERICAL MODELING OF WAVE CLIMATE OVER 25 YEARS

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A first version of a numerical wave data-base along the French Atlantic coasts, the English Channel and the North Sea has been built by hindcasting sea-state conditions over a period of 25 years (1979-2003) with the TOMAWAC wave model. Two sources of wind-data have been considered and two nested grids have been used, in order to reach a resolution of about 3 km along the coasts. The results of the various runs are analysed and discussed, by comparing models' results with buoy data over a period of 2 years (1999 and 2000). From the first version of the data-base statistical analyses are performed in order to build synthetic charts showing average values of the wave climate, as well as wave heights which are exceeded 10 % or 1 % of time. Finally a preliminary estimation of extreme wave heights is tentatively obtained for the coarser model.

1. Introduction – Scope of the study

A research project has been set up with the objective to improve our knowledge of the wave climate along the French Atlantic coasts, in the English Channel and in the North Sea. It aims at building a data-base of continuous series of sea-state parameters (e.g. significant wave height, mean and peak periods, mean direction, directional spreading,…) with high spatial resolution. This is achieved by performing hindcast simulations of wave conditions over a period of 25 years (1979-2003) driven by re-analyzed wind fields.

From these data statistical analyses can be carried out in order to characterize the average wave climate as well as the extreme values of wave height, corresponding to various return periods. Such a data-base will be helpful for a number of applications, e.g. building charts showing wave statistics and areas of potential risks, allowing a better design and reducing costs of sea defenses, obtaining accurate wave climate data for modeling coastal morphodynamics and littoral changes, evaluating available wave power, etc.

The methodology is based on the use of the TOMAWAC spectral wave software applied to two nested grids (Section 2) driven by re-analyses wind-fields which are provided over the models' grids for the target period of time (Section 3). Models' results are compared with buoy data in order to examine the effect of the source of wind data (Section 4) and the influence of model's grid (Section 5). In Section 6 synthetic charts showing average or high values of significant wave height are built by statistical analysis of the hindcast results. Finally a tentative analysis of extreme wave heights is performed in Section 7 on the coarser grid, but this first version still needs to be validated and improved.

2. Description of the numerical models used for the hindcast runs

2.1. *The third-generation spectral wave code TOMAWAC*

The simulations are performed with the third generation spectral wave model TOMAWAC (Benoit *et al.* 1996), which is part of the TELEMAC hydro-informatics suite, developed at EDF-LNHE. TOMAWAC solves the wave action density balance equation (e.g. Bretherton and Garret 1969, Komen *et al.* 1994) and models the evolution (in space and time) of the directional wave spectrum, under unsteady wind forcing. It takes into account the input of energy from the wind, nonlinear wave-wave interactions, as well as dissipation due to white-capping, bottom friction and depth-induced breaking in shallow-water. A feature of high interest of TOMAWAC for nearshore and coastal applications is the use of unstructured spatial grids, which allows to refine the mesh in areas of complex bathymetry and irregular shoreline. The model has already been validated for the hindcast of several real storms (Benoit *et al.* 1996, Aelbrecht *et al.* 1998).

For this project, two nested numerical grids have been set up at different scales (see Sections 2.2 and 2.3). For both models the wave spectrum grid uses 21 frequencies on a logarithmic scale with $\Delta f/f = 0.122$ (between 0.04 Hz and 0.4 Hz) and 36 directions (constant angular resolution of 10 deg.). Output time-step for the results is 1 h. Both models are run with steady-state water levels (corresponding to mean tidal level) and without tidal current effects, although the code may deal with unsteady currents and water levels. Coupled runs with the flow model TELEMAC-2D allowing to study the interactions between waves, tides and storm surges will be addressed in a future phase of this project.

2.2. *The OCEANIC wave model*

The coarser model (called OCEANIC model) covers the northern part of the Atlantic Ocean (30°N to 70°N in latitudes and 50°W to 10°E in longitudes), with a grid of variable mesh size, from about 1 degree offshore down to 20 km along the French coastline (see Figure 1). The spatial grid comprises 2279 nodes and 4218 triangles. No wave spectra are imposed at the boundaries of this model: all the wave energy is generated inside the domain. Some finite depth effects are active in the simulations (refraction, shoaling, bottom friction), but not depth-induced breaking. The computational time-step is 15 min, which permits the simulation of a whole year in about 14 h of CPU time on a basic workstation (model HP 9000/785-C3700 – 750 MHz – 2 Gb RAM).

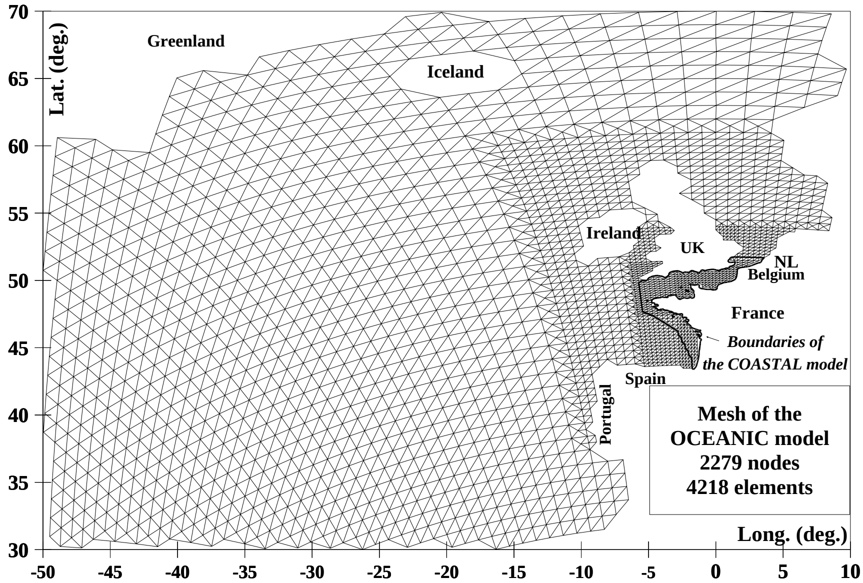

Figure 1 – Spatial mesh of the OCEANIC model.

2.3. *The COASTAL wave model*

The fine model (called COASTAL model) covers the European continental shelf and the English Channel (see Figure 2). The spatial mesh is composed of 5028 nodes and 9261 triangles with a fine resolution of about 2 to 3 km over the nearshore domain and along the French coasts. Shallow-water processes (including breaking) are considered in this model, which uses on its boundaries the directional spectra provided by the OCEANIC model. The computational time-step is 4 min and the required CPU time to model a whole year is about 5 days on the same workstation as mentioned in the previous section.

3. Wind data used for the hindcast runs

Two sources of wind-fields (two components of U_{10}, the speed at 10 m above sea level) are considered and linearly interpolated on the computational grids:

- Winds from the ERA-40 reanalysis from the European Center for Medium-range Weather Forecast (ECMWF). They are provided every 6 hours over a rectangular grid of resolution 0.5 degree, both in latitude and longitude.
- Winds from the NOAA/NCEP reanalysis (version 2), available on Internet (see *www.cdc.noaa.gov/cdc/data.ncep.reanalysis2.html*). They are also provided every 6 hours, but over a much coarser grid (global Gaussian grid T62 which mesh size is about 1.875 degrees).

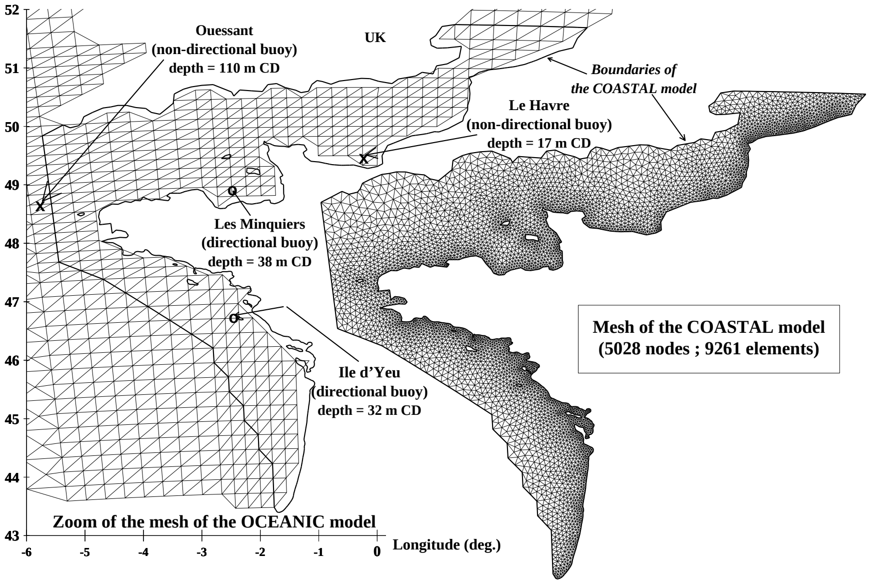

Figure 2 – Mesh of the COASTAL model (right panel) compared with the mesh of the OCEANIC model zoomed near the French coasts (left panel), with the locations of wave buoys used in this study.

4. Effect of the source of wind data (OCEANIC model runs)

In a first step we examine the influence of the source of wind data by performing hindcast runs over a period of 2 years (1999 and 2000) with the OCEANIC model only. In both cases, all options and parameters of TOMAWAC (time-step, source and sink terms, etc.) are the same, the only difference being the wind fields, either ECMWF or NCEP2 winds.

A brief comparison of the two sources of wind data revealed that the NCEP2 wind speeds are in general higher than the ECMWF ones, and this is particularly noticeable for the highest wind speeds. In order to use the wave model with the same settings and parameters, we decided to apply a correction factor to the wind speeds. After some tests and calibration runs, the ECMWF winds were increased by 2 % to 10 % depending on the wind speed U_{10}, and the NCEP2 winds were reduced by 10 % uniformly.

Models' results (in particular the significant wave height H_{mo}, the mean period $T_m = T_{02}$ and the main incoming wave direction θ_m) are compared with measurements from buoys of the French network operated by the CETMEF. Four measuring buoys are considered in this paper: two of them are directional wave buoys (Ile d'Yeu and Les Minquiers) and the two other ones are non-directional buoys (Ouessant and Le Havre). The locations of these buoys are indicated on Figure 2. Two of them are exposed to waves and swell coming from the Atlantic Ocean and are located in deep water (Ouessant, 110 m CD) or intermediate water depth (Ile d'Yeu, 32 m CD). The buoy of Les Minquiers is located in the western part of the Channel, still in intermediate water depth (38 m CD), while the buoy of Le Havre lies in the middle of the Channel, closer to the shore and in more shallow water conditions (17 m CD). Table 1 shows the periods of time where buoy data are available over the years 1999 and 2000.

Table 1. – Schematic view of the periods where data are available for the 4 wave buoys of CETMEF used for evaluation of model's results

	1999												2000											
Ouessant								■	■	■			■	■	■	■	■	■	■	■	■	■	■	■
Ile d'Yeu	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Les Minquiers	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
Le Havre	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

As an example of results, time series of H_{mo} and T_m are plotted on Figure 3 for the last quarter of year 1999 at the two buoys Ile d'Yeu and Les Minquiers.

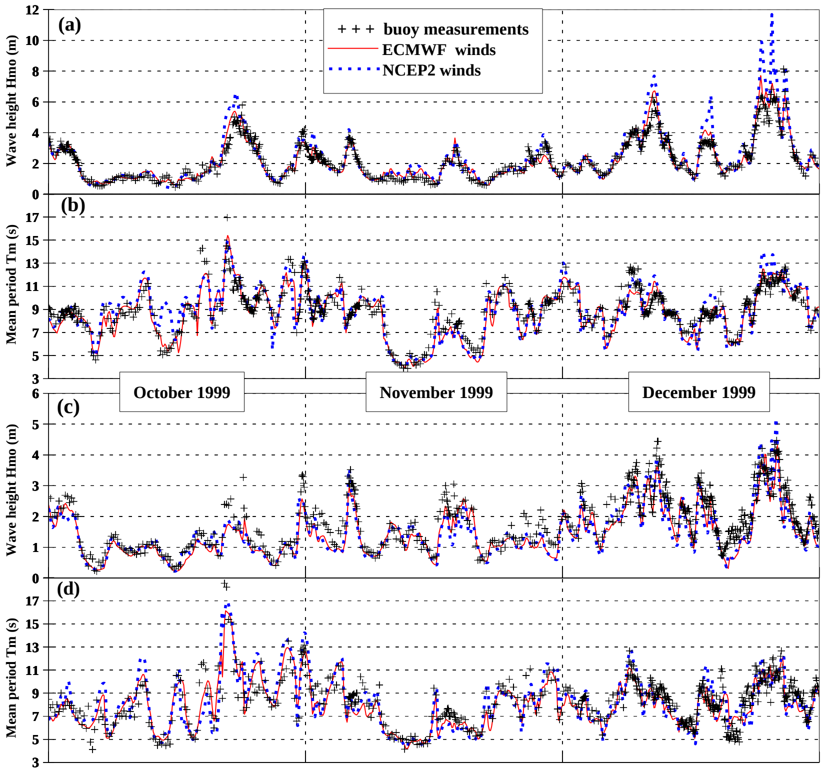

Figure 3 – Comparison of model's results with buoy data for the last quarter of year 1999.
a) Hmo at Ile d'Yeu ; b) Tm at Ile d'Yeu ; c) Hmo at Les Minquiers ; d) Tm at Les Minquiers.

The time series of both H_{mo} and T_m are fairly well reproduced by the model, with the two sources of wind data. One can note that the largest peaks of computed H_{mo} are higher for the NCEP2 winds than for the ECMWF winds (in particular during the storms of the end of December 1999). The evolution of the computed mean period compares favorably with the measured one, even for a succession of swell and wind-sea events (see Figure 3.d at Les Minquiers).

However such temporal profiles of wave parameters do not permit a detailed and quantitative comparison of model's performances. To that end so-called Q-Q plots are drawn which show the correspondence between measured and computed quantiles (from 1 % to 99 %) of the statistical distribution of H_{mo} over the two years 1999 and 2000 (see Figure 4). We also compute some quantitative measures of the agreement between the measured and computed times series of H_{mo} (see Table 2). The analysis of this information clearly confirms that the wave heights obtained from the NCEP2 winds are higher than the ones obtained from ECMWF winds. This is particularly noticeable for the locations exposed to Atlantic wave climate (Ouessant and Ile d'Yeu), whereas the differences for the buoys located inside the Channel are significantly weaker. The differences between measurements and model's results at Ouessant are partly explained by some limitations of the buoy (this was checked and confirmed by CETMEF).

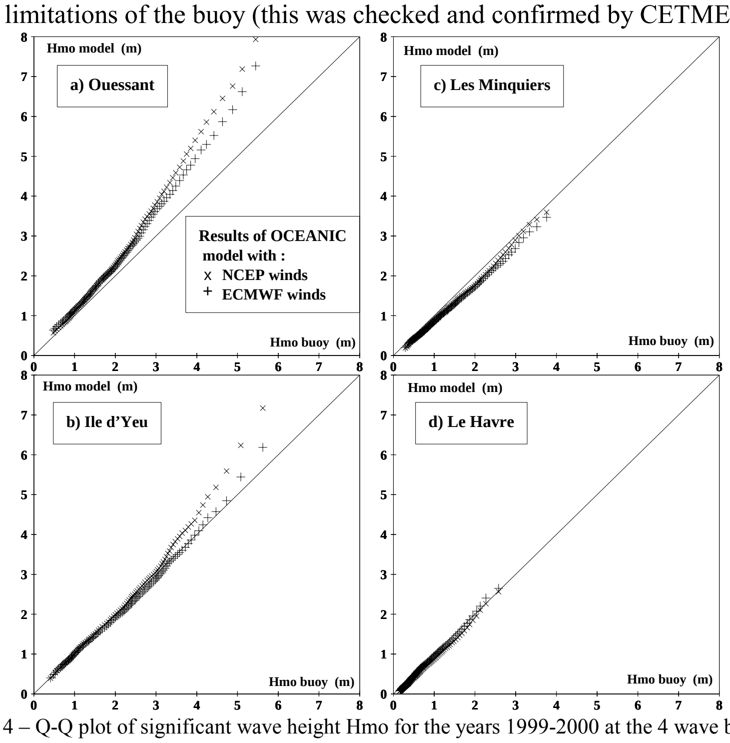

Figure 4 – Q-Q plot of significant wave height Hmo for the years 1999-2000 at the 4 wave buoys.
a) Ouessant ; b) Ile d'Yeu ; c) Les Minquiers ; d) Le Havre.

Table 2. – Quantitative measures of model's performance on the variable Hmo for the 4 wave buoys for the years 1999-2000

	Mean absolute error (m)		**Root mean square error (m)**		**Slope of the regression line**	
Winds	**ECMWF**	**NCEP2**	**ECMWF**	**NCEP2**	**ECMWF**	**NCEP2**
Ouessant	0.45	0.57	0.63	0.88	1.24	1.39
Ile d'Yeu	0.27	0.37	0.37	0.59	0.98	1.11
Les Minquiers	0.25	0.27	0.33	0.37	0.87	0.90
Le Havre	0.19	0.24	0.27	0.34	0.93	0.84

In general the comparison with buoy data is also better for the results obtained with the ECMWF winds as it can be seen from Table 2. The mean absolute error and the root mean square error at the four buoys are lower when ECMWF winds are used. The slope of the regression line does not reflect any systematic bias in the model. It is closer to 1 for the results obtained with ECMWF wind fields, except at Les Minquiers where the OCEANIC model tends to slightly underestimate the wave height. It is likely that the results obtained with the NCEP2 winds could be improved by further correction of the wind speeds or calibration of the wave model, but this was not undertaken in the frame of this project. It should also be reminded that the mesh size of NCEP winds is almost 4 times the one of ECMWF winds (see Section 3).

One should also note that the results obtained at Le Havre (in rather shallow water, 17 m CD) and with this coarse grid (see Figure 1) are remarkably good compared with buoy data. Such a good agreement was not expected from the OCEANIC model, but it indicates that its results may still be used with confidence even quite close to the coast.

On Figure 5 a similar Q-Q plot is presented for the mean wave period over the years 1999-2000. A very good agreement is observed at the directional buoys of Ile d'Yeu and Les Minquiers. The effect of the source of wind is weak. In general the mean periods obtained from NCEP2 winds are a little bit higher. Limitations of the buoys regarding the range of recorded periods explains to a large extent the different pattern observed at Ouessant and Le Havre. At Ouessant for instance, it can be seen from Figure 5.a that the periods measured by the buoy do not exceed 10 s which is obviously not the case in reality as this location is largely exposed to Atlantic swell. Similarly the buoy at Le Havre does not indicate periods higher than 7 s which again are known to sometimes occur.

Finally for the mean wave direction (analyzed at the directional buoys of Ile d'Yeu and Les Minquiers only) good and very similar results are obtained from the two sources of winds, but are not presented here.

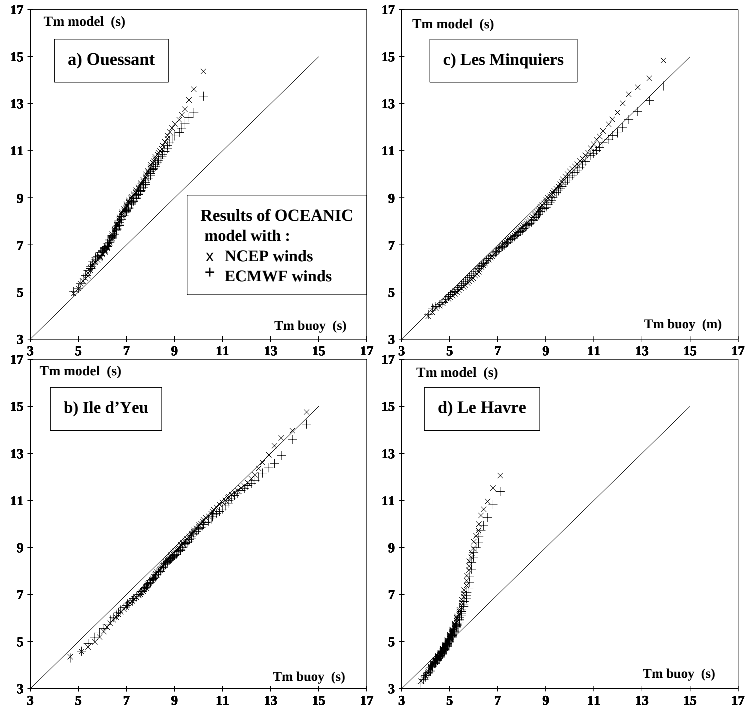

Figure 5 – Q-Q plot of mean period Tm for the years 1999-2000 at the 4 wave buoys.
a) Ouessant ; b) Ile d'Yeu ; c) Les Minquiers ; d) Le Havre.

5. Improvements brought by the COASTAL grid (ECMWF winds only)

We then examine the influence of using a finer grid, namely the COASTAL model (see Section 2.3 and Figure 2) driven at its boundaries by wave spectra computed by the OCEANIC model. For this purpose we only present one case corresponding to the year 1999 and the use of ECMWF wind fields. The COASTAL model uses the same physical parameters and options as the OCEANIC model except that depth-induced breaking is activated (formulation of Battjes and Janssen 1978). The time-step is decreased to 4 min to accommodate for the finer mesh size.

Although time series of various parameters can again be plotted, we only present below the Q-Q plots for the wave height H_{mo} at the 3 buoys of Ile d'Yeu, Les Minquiers and Le Havre (see Figure 6). The most offshore buoy of Ouessant is outside the grid of the COASTAL model. The analysis of this figure shows that there is almost no differences between the two models for the location of Ile d'Yeu. This is not surprising for two reasons: first, this area is characterized by intermediate water depths (32 m CD) where shallow water effects are not expected to be significant and, second, its exposition to incoming waves from the Atlantic Ocean is very well resolved by the OCEANIC grid.

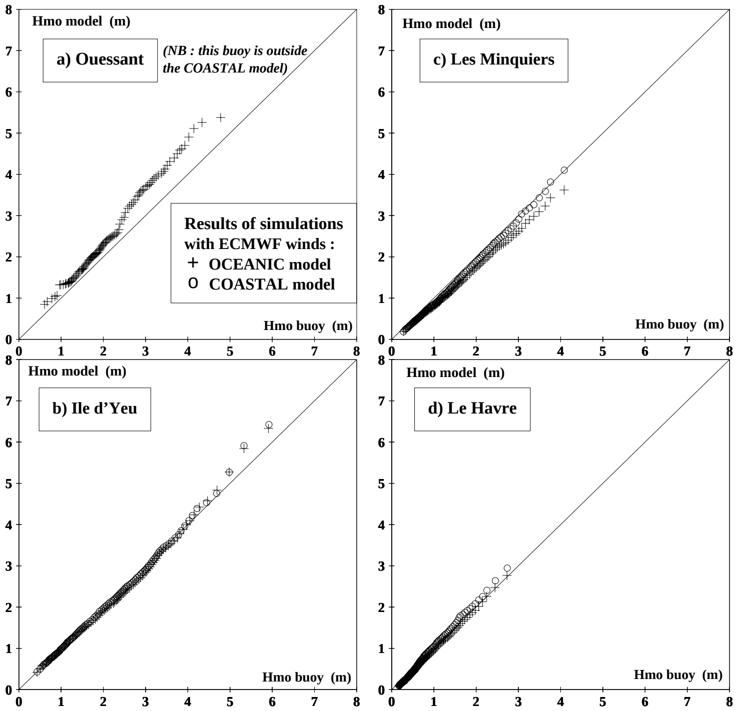

Figure 6 – Q-Q plot of significant wave height Hmo for the year 1999 at the 4 wave buoys.
a) Ouessant ; b) Ile d'Yeu ; c) Les Minquiers ; d) Le Havre.

At the location of Les Minquiers (see Figure 6.b) the computed wave heights are greater with the COASTAL model and the agreement of model's results with buoy data is significantly improved, even for the highest sea-states of the distribution. In this case the better representation of the maritime domain and its bathymetry brought by the COASTAL grid is evident. Finally at Le Havre we again note an increase of the wave heights in the results of the COASTAL model. There the computed wave heights are a little bit higher than the measured ones but the overall agreement remains good.

6. Synthetic charts of some representative wave heights

At the present stage of the project not all the ECMWF wind data over the period 1979-2003 were available to us for the hindcast runs, so we only performed the first complete hindcast run over this period of time with the NCEP2 wind data, although we found in Section 4 that better results were obtained with ECMWF wind data over a limited period of time. The first version of the complete hindcast simulation (termed NCEP2_A) must thus be regarded as preliminary and will be completed soon by similar hindcast runs driven by ECMWF winds.

Simulations results are presented here for the OCEANIC grid only. Results on synthetic wave parameters (H_{mo}, T_m, θ_m,…) are stored at each node of the computational grid every hour over the 25 years. Then a statistical analysis is automatically performed at each node so as to determine the histogram of each wave parameter, the joint distribution of H_{mo} and T_m, or H_{mo} and θ_m, etc. as it is usually done for buoy data in order to prepare synthetic plots describing the wave climate. Here we present some results from the statistical analysis of the distribution of the wave height H_{mo}. Figure 7 presents two plots representing average wave heights: the (arithmetical) mean of H_{mo} over the whole period (see Figure 7.a) and the median value of H_{mo} (value which is exceeded half of time) (see Figure 7.b). The spatial distribution of these two wave heights is quite similar with a difference of about 0.3 to 0.6 m over the plotted area, the median height being lower than the mean height.

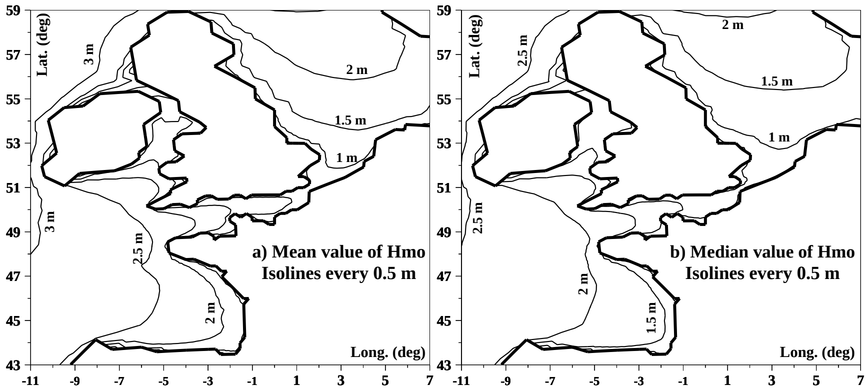

Figure 7 – Charts of the mean value (a) and median value (b) of wave height Hmo computed over the period 1979-2003 with the OCEANIC model driven by NCEP wind fields.

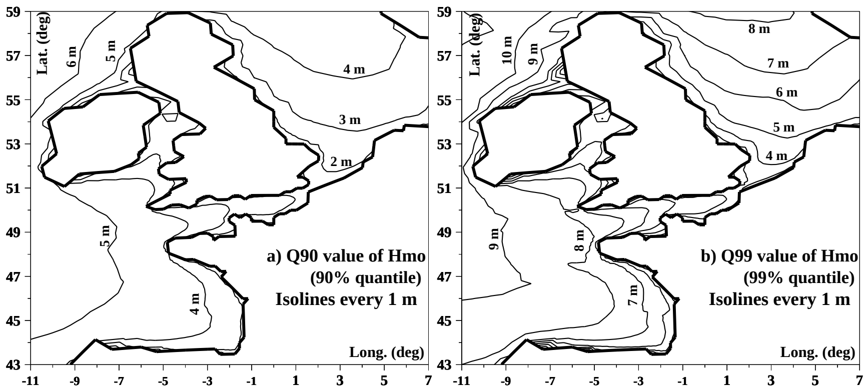

Figure 8 – Charts of the Q90 value (a) and Q99 value (b) of wave height Hmo computed over the period 1979-2003 with the OCEANIC model driven by NCEP wind fields.

In addition to these average wave heights other interesting wave heights can be computed from the simulated distribution of wave heights. In particular it is possible to draw plots of Qnn value of wave height (nn lying between 0 and 100) which corresponds to the value which is not exceeded nn % of time (or which is exceeded (100-nn) % of time. To illustrate this we present on Figure 8 charts corresponding to the Q90 and Q99 values of H_{mo}, i.e. the values which are exceeded only 10 % and 1 % of time respectively. This kind of figures provides a quick overview of the highest computed sea-sates conditions over the European continental shelf, the Bay of Biscay, the Channel and the North Sea. The general pattern is quite similar between the two plots of Figure 8, but the wave heights are significantly higher for the Q99 wave height: there is a factor of about 1.7 to 2 between the H_{mo}_Q90 et H_{mo}_Q99 over the plotted area.

7. Tentative estimation of extreme wave heights

In the previous section we considered the largest wave heights over the simulated period. Another point of interest is the estimation of extreme values of wave heights, which have a return period higher than the duration of the available sample. This is a frequent question in marine engineering. Specific extreme value analysis methods have been developed to perform this extrapolation and are currently applied to buoy data (e.g. Mathiesen et al. 1994, Goda 2000). Although, as already mentioned in the previous section, more reliable hindcast results are expected from the ongoing runs driven by the ECMWF wind fields, we tentatively apply the extreme value analysis to the results obtained over the period 1979-2003 with the NCEP2 wind data, so has to have a first insight on the distribution of extreme wave heights.

The methodology used for this purpose is based on the following steps (automatic treatment of all grid nodes of the OCEANIC model):

- Selection of samples of storm events. We use the Peaks Over Threshold (POT) method to build a set of storm events. The threshold H_o for H_{mo} is node-dependent and is chosen as the Q95 value of the local distribution of H_{mo} (the value which is exceeded only 5 % of time). With this threshold 250 to 400 events are selected over the 25 years period (i.e. 10 to 16 events per year). It was also checked that these events are independent.
- Fit of a distribution of wave heights. Somewhat arbitrarily we selected a two-parameter Weibull model for the distribution of the significant wave height H_{mo}:

$$F(H) = 1 - \exp\left(-\rho(H - H_o)^P\right)$$

A Maximum Likelihood Method is used to determine the shape parameter P and the scale parameter ρ of the distribution at each grid-point.

- <u>Compute the values of significant wave height for given return periods</u> and the associated confidence interval. For the Weibull distribution the wave height H_T which has a return value of T years is obtained as:

$$H_T = H_o + \left(\frac{1}{\rho} \ln(12\mu.T) \right)^{1/P}$$

where μ is the average number of storm events per month (or 12 μ is the average number of storm events per year).

Examples of results obtained along these lines are presented on Figure 9 for the significant wave height which has a return period of 50 years (twice the duration of the sample). For the reasons stated above, it is emphasized that the results are provisional and need to be compared with results obtained from the ECMWF wind data and with extrapolation performed from buoy data as well.

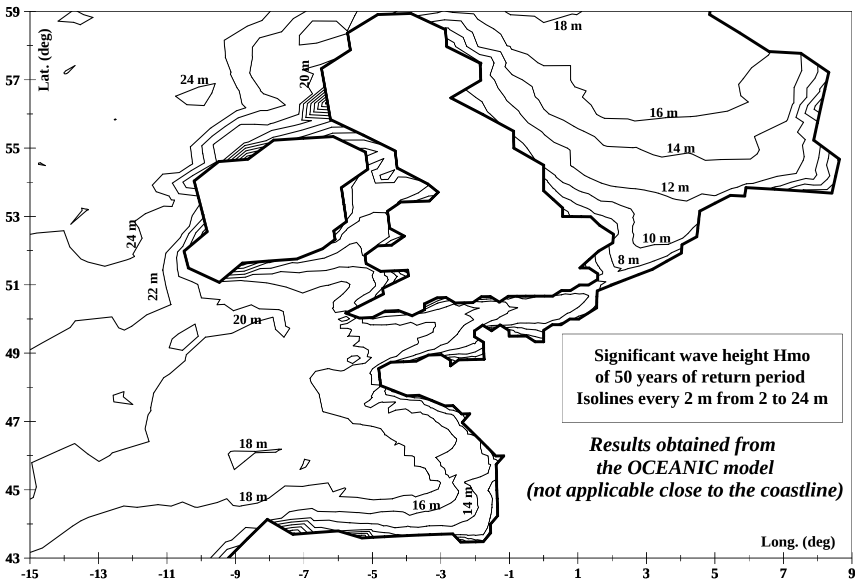

Figure 9 – Chart of the extreme wave height with return period of 50 years computed over the period 1979-2003 with the OCEANIC model driven by NCEP wind fields.

8. Conclusions and future work

With the aim of producing a continuous data-base of sea-states along the coasts of France, in the Channel and the North Sea by hindcast over the period 1979-2003, two efficient numerical models (OCEANIC and COASTAL models) have been built and calibrated on the basis of the third-generation wave code TOMAWAC.

Several sensitivity runs have been performed, some of them being outlined in this paper. Two sources of re-analyzed wind data were considered (ERA-40 re-analysis from ECMWF and version 2 of the NOAA/NCEP reanalysis) and it was shown by comparison with buoy measurements over a period of 2 years that better results are obtained with ECMWF winds (wave heights seem to be overestimated in the results obtained with NCEP winds). We also noted that the COASTAL model improves the results of the OCEANIC model in particular inside the Channel or close to the coastline, when the contour of the maritime domain and/or the bathymetry are not well resolved by the coarser grid.

A first version of the hindcast results over 25 years is available for the OCEANIC grid (resolution of 20 km along French coasts) on the basis of NCEP winds. Procedures for statistical analysis have been developed which allow to draw charts of various wave heights, representative of the local wave climate.

Ongoing work deals with the simulation of the 25 years period with the COASTAL model driven by ECMWF winds, with particular examination of shallow water effects. Next, statistical treatments of results such as those presented in the paper will be performed for both models (average wave climate and extreme values of wave heights associated with different return periods).

Acknowledgements

This project is a joint collaboration between EDF-LNHE, CETMEF and Meteo-France. The authors gratefully acknowledge the financial support of the French Ministry in charge of the Sea, through the CETMEF (Grant n°02000322).

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KEYWORDS – ICCE 2004

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Abstract number 160   (paper number 189 at the Conference)

Waves
Wind waves
Wave climate
Wave models/modeling
Numerical models/modeling
Wave hindcast/forecast
TOMAWAC
Waves statistics
Extreme wave statistics
Energy balance equation