XVIIèmes Journées Nationales Génie Côtier – Génie Civil
Chatou, 2022
DOI:10.5150/jngcgc.2022.019 *© Editions Paralia CFL*
disponible en ligne – http://www.paralia.fr – available online

Assessment of the ANEMOC-3 sea state hindcast database for modelling a series of energetic winter storms along the French coast

Maria TELES [1], Morgane WEISS [1], Michel BENOIT [1,2]

1. EDF R&D, Laboratoire National d'Hydraulique et Environnement (LNHE), Chatou, France.
   maria.teles@edf.fr, michel.benoit@edf.fr
2. Laboratoire d'Hydraulique Saint-Venant LHSV (Ecole des Ponts ParisTech, EDF R&D), Chatou, France.

Abstract:
In the last decade, a period of extreme storm conditions, the 2013-2014 winter, occurred in the north-eastern Atlantic Ocean and impacted significantly the French coasts. Several energetic events were recorded, in deep and intermediate water depths.
In the present work, the main purpose is to model those events with the 3rd generation wave model TOMAWAC (BENOIT *et al.*, 1996), in the framework of the construction and calibration of the version 3 of the ANEMOC sea state database (see RAOULT *et al.*, 2018) for a progress report in the building of this database).
The wave numerical database is built using two computational grids: one at a larger scale, covering the whole Atlantic Ocean (up to 0.15° mesh resolution), and a second one, nested into the former, covering the Atlantic, the English Channel and North Sea French coast (up to 0.01° mesh resolution). The wave-tide-current interactions are considered in the later model. The wave generation and propagation, as well the hydrodynamic calculations are modelled through the forcing of CFSR (1979-2010) and CFSv2 (2011-2021) wind fields reanalyses, available with a spatial resolution of 0.3° and 0.2° respectively, and a time step of 1 h.
The numerical results are compared with buoy measurements during the energetic period of the winter season 2013-2014 taken offshore and approaching the French coast, with sensitivity analysis regarding different physical processes involved in the wave generation and propagation modelling, models' resolution and interaction of waves with tidal currents. A particular attention is devoted to improving the performance of the model to simulate the extreme significant wave heights recorded at the peaks of the various storms.

Keywords:
Wave numerical hindcast; Wave climate; Storm waves; ANEMOC-3; TOMAWAC, TELEMAC-2D, Tidal water levels and currents effects, Energetic events.

1. Introduction

The knowledge and understanding of usual (or mean) and extreme sea state climatology is essential for marine and coastal engineers or scientists, for a number of purposes, such as the design of coastal protection structures, offshore wind turbines and industry or to model morphodynamical processes, such as erosion or deposition of sediments.
For that purpose, one can count on in situ (usually wave buoys) and/or satellite altimetry data, with which the sea states can be characterized. Nevertheless, most often, there is no wave parameter measurements available over a long and continuous time period and/or within a spatial mesh with fine resolution near the coast.
A hindcast wave database overcomes these limitations by providing complete time series of wave parameters and/or full wave spectra with a fine spatial resolution. That is one of the reasons that led EDF R&D LNHE together with the Cerema to develop the hindcast wave numerical database ANEMOC about 16 years ago (ANEMOC is the French acronym of Atlas Numérique d'Etats de Mer Océanique et Côtier) with main interest devoted to the French coastal areas of the Atlantic Ocean, English Channel and North Sea (BENOIT *et al.*, 2008). Subsequently, different extensions and mesh domains have been produced, covering the Mediterranean Sea, the French West Indies and the Caribbean Sea, the Reunion Island in the Indian Ocean, and the Pacific Ocean (figure 1).
All these ANEMOC databases are built with the help of the third-generation spectral wave model TOMAWAC (BENOIT *et al.*, 1996), part of the TELEMAC-MASCARET numerical platform.

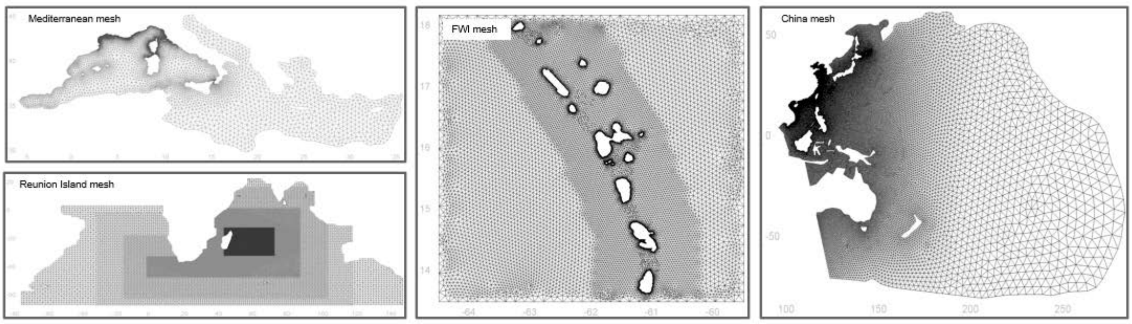

Figure 1. ANEMOC mesh domains (Mediterranean Sea, Reunion Island, French West Indies and Pacific Ocean).

In the present paper, we focus on the ANEMOC Atlantic Ocean domain, presented in section 2, followed by a brief description of the winter season 2013-2014 in section 3. In section 4, analysis and comparisons between numerical results and *in situ* and altimeter measurements are shown and finally some concluding remarks are drawn in section 5.

2. ANEMOC hindcast wave numerical database

ANEMOC Atlantic Ocean was first developed by EDF R&D (BENOIT & LAFON, 2004; LAFON & BENOIT, 2006) ant then in collaboration with Cerema (BENOIT *et al.*, 2008), with the construction of two model domains: a so-called 'oceanic' domain covering the whole Atlantic Ocean and a so-called 'coastal' domain, located along the Atlantic, English Channel and North Sea French coasts, covering the period 1979-2002. Later, a second version, called ANEMOC-2, was developed (LAUGEL *et al.*, 2014) with mesh improvements and hourly wind forcing fields from CFSR reanalysis. This later version was calibrated with 9 years of altimeter satellite data and validated extensively against *in situ* buoy measurements along the French coast.

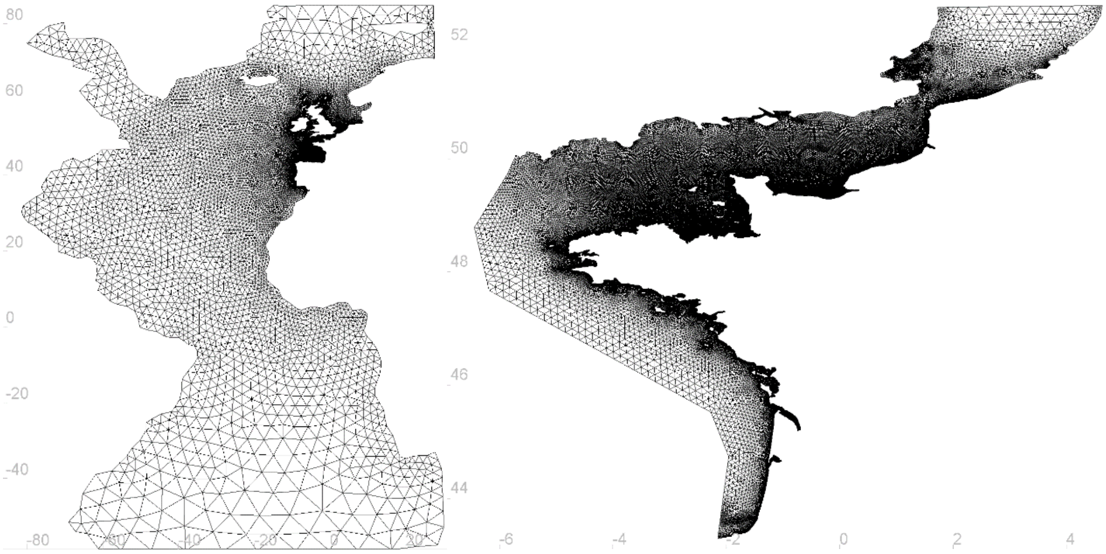

Figure 2. ANEMOC-3 oceanic (left panel) and coastal (right panel) domains.

More recently, a third version, called ANEMOC-3, was initiated with mesh improvements and incorporation of tidal water levels and currents effects during wave propagation within the coastal domain (RAOULT *et al.*, 2018). Figure 2 presents the oceanic (on the left) and coastal (on the right) domains with approximately 20 km and 1 km spatial resolution, respectively, near the European and French coastline. The calculations from the oceanic domain give the boundary conditions to the coastal domain with a 1-h time period.

ANEMOC-3 is built using TOMAWAC for the sea state simulations and the hydrodynamic circulation model TELEMAC-2D for the flow induced with the tides (with account of atmospheric effects leading to possible storm surges), both part of the TELEMAC-MASCARET numerical platform.

While TOMAWAC is run on both oceanic and coastal domains, TELEMAC-2D is run on the coastal domain only, such that tidal water levels and currents are computed and updated in TOMAWAC coastal domain every 15 min.

The bathymetry maps for both oceanic and coastal domains are interpolated on each mesh from LEGOS (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France) data which has 800 m resolution. For the oceanic domain the area is not covered by the later (namely the Southern and North-Eastern zones) being completed with GEBCO (General Bathymetric Chart of Oceans) data with 30 arc-second resolution.
Regarding the atmospheric forcing, winds at 10 m elevation and sea-surface pressure values are taken from NOAA reanalysis CFSR data (https://rda.ucar.edu/datasets/ds093.1/) from 1979 till 2010, with nearly 0.3° spatial resolution, and from its extension CFSv2 data (https://rda.ucar.edu/datasets/ds094.0/) from 2011 till 2021, with nearly 0.2° spatial resolution. Wind values are then interpolated on both oceanic and coastal domain grids and pressure values on the coastal grid to force the hydrodynamic circulation model.
TOMAWAC solves the wave action balance equation with a spectral discretization of 32 frequencies from 0.0345 Hz (wave period of 29 s) to 0.6622 Hz (wave period of 1.5 s) and 36 directions (angular resolution of 10°), and a time step of 5 min for the oceanic domain and 30 s for the coastal domain.
Regarding the physical processes considered, the so-called BAJ formulation (BIDLOT *et al.*, 2007) is used, in which the wind generation is parametrized with Janssen's model (JANSSEN, 1989; 1991), the whitecapping dissipation is taken from KOMEN *et al.* (1984) (with dissipation coefficient =2.1 and weighting coefficient =0.4) and nonlinear quadruplet transfers are evaluated with the Discrete Integration Approximation (DIA) method (HASSELMANN & HASSELMANN, 1985). Bottom friction is considered through BOUWS & KOMEN (1983) parametrization. In the BAJ formulation, the wind coefficient β_m was changed to $\beta_m = 1.1$ after wave numerical results calibration (RAOULT *et al.*, 2018).
In the coastal domain the depth-induced breaking is considered with Thornton and Guza's model (THORNTON & GUZA, 1983) and the wave dissipation due to opposing currents with VAN DER WESTHUYSEN (2012) formulation.
The tidal levels and currents are computed with the hydrodynamic model TELEMAC-2D. The boundary conditions are extracted from the North-East Atlantic (NEA) atlas with 47 harmonic components (http://ctoh.legos.obs-mip.fr/data/coastal-products/tidal-constants/nea). The bottom friction coefficient from Chezy formulation is set to 70 $m^{1/2}/s$ and the velocity diffusion coefficient to 10^{-6} m^2/s. The wind drag coefficient varies with wind velocity as proposed by FLATHER & DAVIES (1975).
ANEMOC-3 gives 30 min period output of wave parameters such as spectral significant wave height H_{m0}, mean wave periods $T_{m-1,0}$ and T_{m02}, peak period T_p, direction spreading σ, the mean wave direction Dir_m and mean wave power (per meter of length crest).
Recently, ANEMOC-3 was extended to cover the period 1979-2021, giving 43 years of wave hindcast in total.

3. Series of 2013-2014 winter storms

In order to evaluate the capability of ANEMOC-3 to model both regular (mean) and extreme sea states, the 2013-2014 winter season was chosen because many storms occurred during this period that impacted severely the French coasts, mostly the Atlantic front. As an example, figure 3 shows the time series of significant wave height recorded at the Brittany buoy (UKMO 62163), located offshore Brittany in the Atlantic Ocean. We can see that, in the first 15 days of February 2014, H_{m0} remained higher than 4 m, with high peak values reaching 13-14 m. In this 2-month period January-February 2014 alone, 6 storms have their peak H_{m0} values exceeding 10 m at this location.

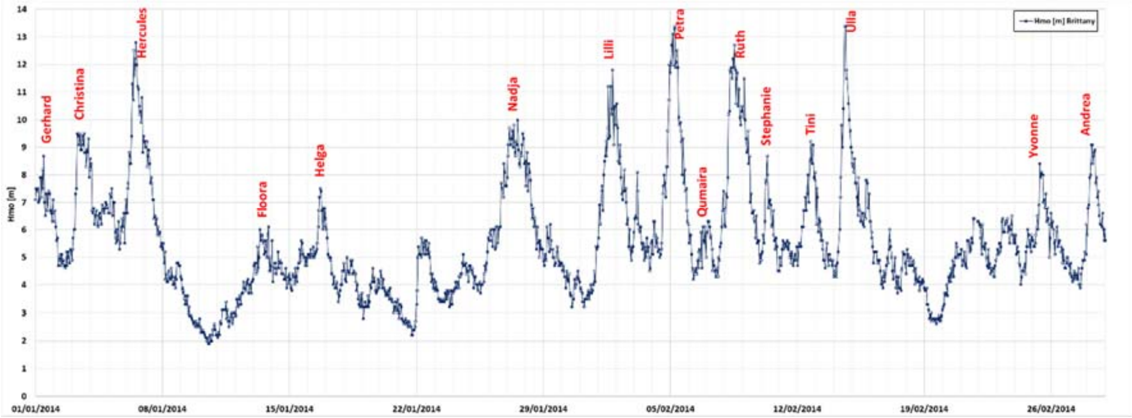

Figure 3. Significant wave height evolution during the months of January and February 2014 measured at Brittany buoy (62163).

4. Results and analysis

To assess and validate TOMAWAC calculations and ANEMOC-3 quality of results, we compare them with the datasets produced by buoy and altimeter observations, presented in the following sub-sections.

4.1. <u>Wave buoys</u>

We collected *in situ* wave parameters from wave buoys from the CANDHIS (France), UKMO and the Agency for Maritime Services and Coast – Flemish Government (Belgium) observational networks. Both offshore (deep water) and coastal buoys were selected (water depths ranging from 20 m to 4300 m). In the following, only a limited part of the comparisons made are presented, focusing on the following buoys: Gascogne (UKMO 62001), Pierres Noires (CANHIS 02911) and Belle-Ile (CANDHIS 05602), all placed in the Atlantic Ocean, and Westhinder, placed in the Eastern part of the English Channel. Figure 4 presents in the upper panel the comparisons of the time series of significant wave height (H_{m0}) recorded (in black) and obtained by ANEMOC-3 oceanic domain (in blue), at the offshore buoy Gascogne (62001), located in deep waters (4300 m depth). This buoy is outside the area coved by the coastal domain. We can observe a good agreement of the numerical results with the measurements, with a slight overestimation for the most energetic events though. This can be confirmed by the scatter plot represented in the lower panel between observed versus modelled significant wave height results and the superposed Q-Q (quantile-quantile) plot (in black). A general good agreement is found, including the largest wave heights (again slightly overestimated), with relatively low statistical errors (e.g. bias of 0.08 m and Scatter Index (SI) of 11.6 %).

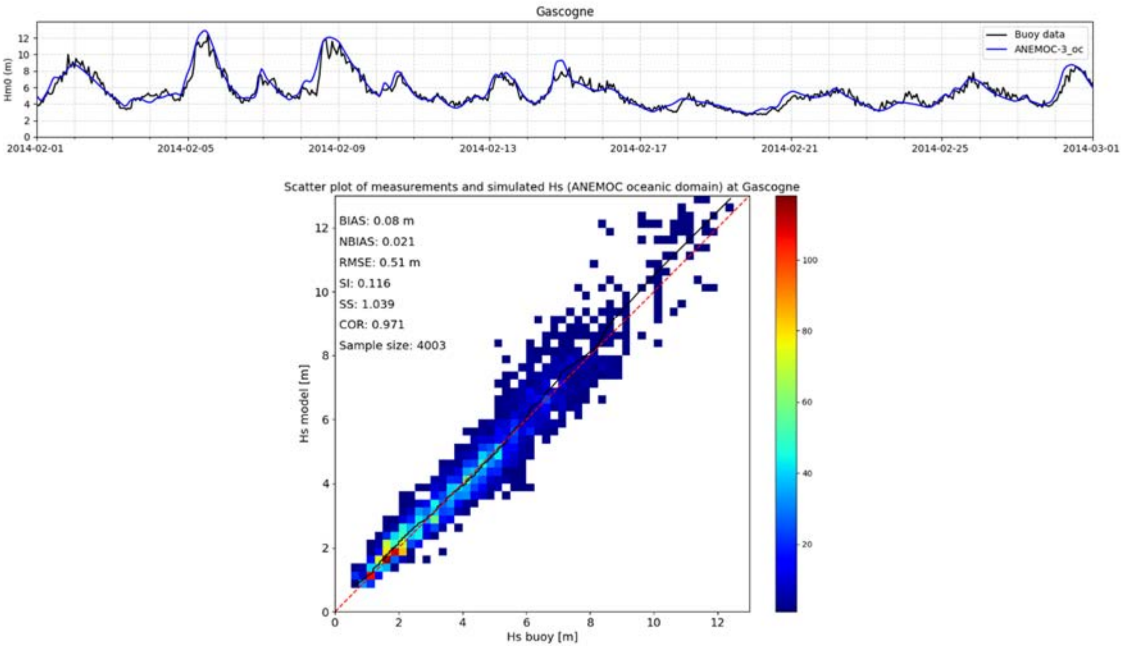

Figure 4. Comparison of H_{m0} time series measured and modelled at the ANEMOC-3 oceanic domain at Gascogne buoy (62001) over the month of February 2014 only (upper panel) and scatter plot of H_{m0} over the 6-month period (lower panel).

Model-data comparisons at Pierres Noires buoy (CANDHIS 02911, placed at 60 m depth) are presented in figure 5. The comparisons include the results from the oceanic model (blue curves) and the coastal model with (in yellow) and without (in red) tidal current effects included over the month of February 2014. Four wave parameters are shown: the significant wave height (H_{m0}), the mean wave period ($T_{moy} = T_{m-1,0}$), the peak period (T_p) and the mean wave direction (Dir) against measurements. There is an overall very good behaviour from the numerical model results for each of the calculated wave parameters. Regarding H_{m0}, the highest values reached at the storm peaks are in general a bit lower from the coastal model in comparison with the oceanic one (which shows a slight trend in overestimating these peak values). There is a slight improvement when tidal currents are considered in wave propagation, with modulation effects present in this case for the selected wave parameters. Nevertheless, the amplitudes of these modulations in the simulations are generally lower than the measured ones.

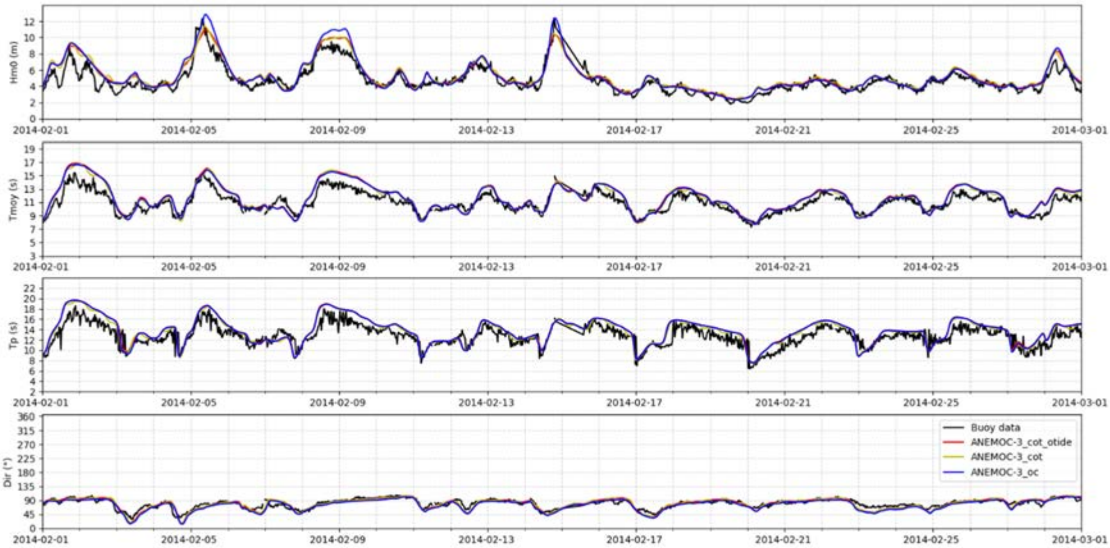

Figure 5. Comparison of H_{m0}, T_{moy}, T_p and Dir time series measured and modelled by the ANEMOC-3 oceanic (blue) and coastal domains with (yellow) and without current effects (red) on the coastal domain at Pierres Noires buoy (02911) over February 2014.

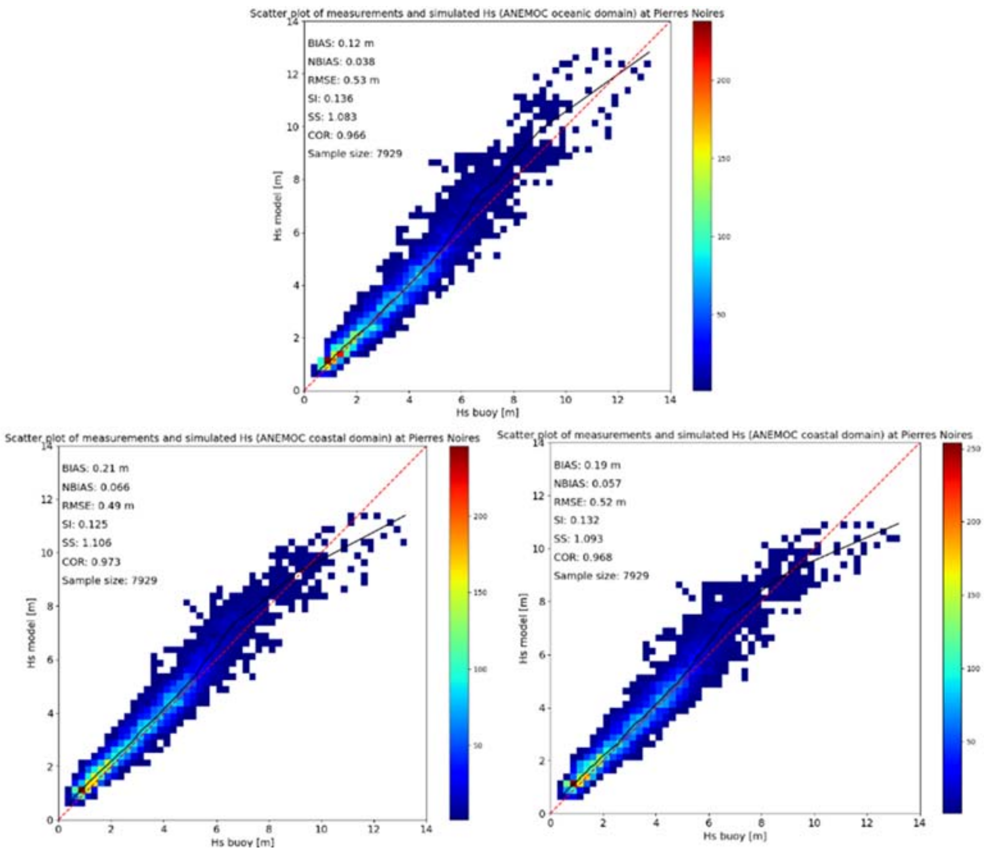

Figure 6. Scatter plot and Q-Q plot of modelled versus measured H_{m0} from the oceanic (upper panel) and coastal (lower left panel) ANEMOC-3 domains and modelled considering only tidal water levels in the coastal domain (lower right panel) at Pierres Noires buoy (02911).

The good agreement between measurements and modelled wave heights can be confirmed by the scatter and Q-Q plots for the oceanic (top panel of figure 6), and coastal domain with tidal effects accounted for (lower left panel of figure 6) domain, giving more evidence of a slight underestimation of the most extreme events.

When tidal currents are not considered (lower right panel of figure 6), the SI is 13.2 % and increases relatively to the simulation with tidal current included (SI = 12.5 %), but it remains smaller than with the oceanic domain results (SI = 13.6%). This confirms that not only the mesh resolution has an impact on the results, due to a better representation of bathymetric features, but also that the tidal current effects are significant at this location.

At Belle-Ile buoy (CANDHIS 05602), located around 45 m depth, we have also a good agreement of the different wave parameters evolution over this period for both oceanic and coastal domains (time series not shown here), with good statistical error indicators in the order of 11% for the SI as shown in figure 7. The improvement from oceanic to coastal domain is less marked at this location, but all skill scores are improved (e.g. bias reduced from -0.08 m to -0.02 m).

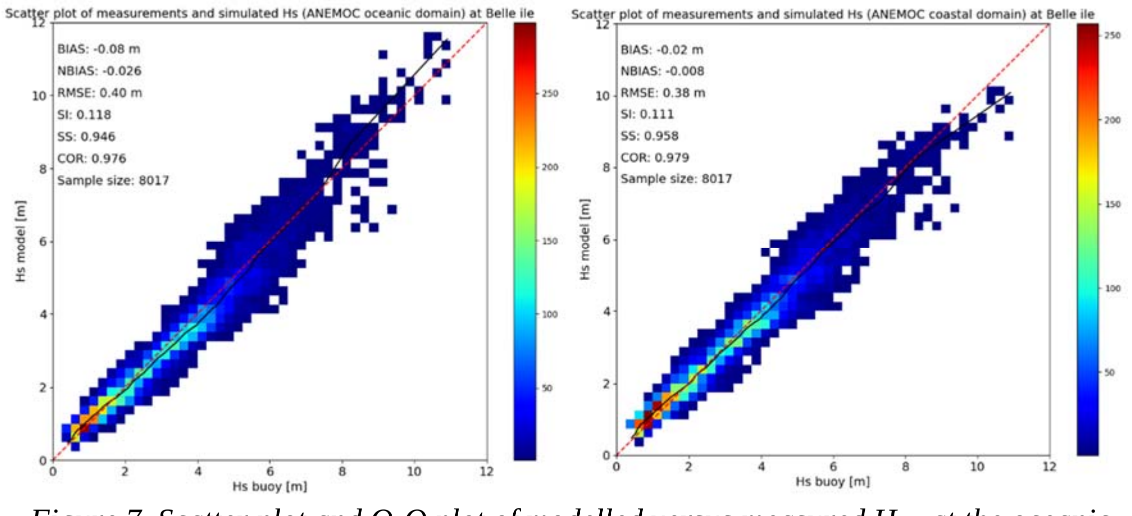

Figure 7. Scatter plot and Q-Q plot of modelled versus measured H_{m0} at the oceanic (left) and coastal (right) ANEMOC-3 domains at Belle-Ile buoy (05602).

At the Westhinder buoy, the time series of wave height for both oceanic (in blue), and coastal domains, with (yellow) and without tidal currents effects (in red), against measurements (in black) are presented in figure 8. An overall good agreement is found for oceanic and coastal domains, with a slight overestimation of the wave height calculated with the oceanic domain over the time period presented.

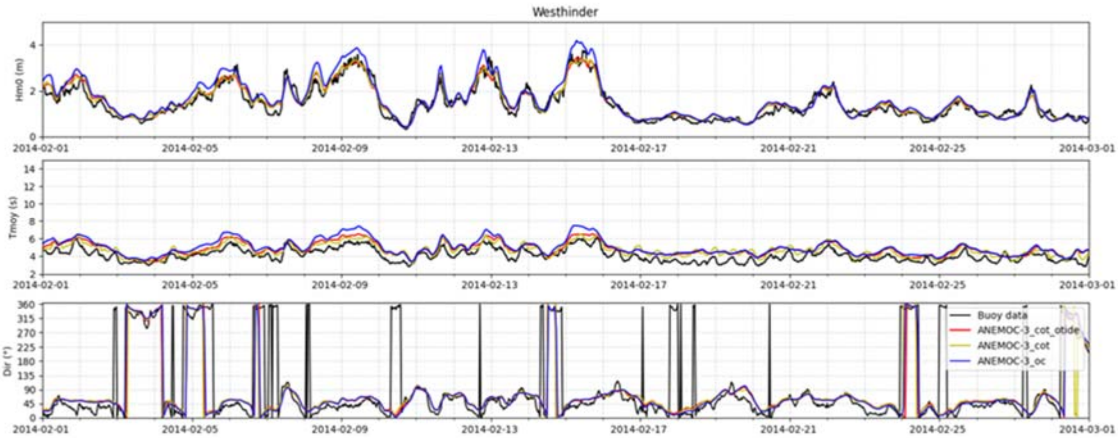

Figure 8. Comparison of H_{m0}, T_{moy} and Dir time series measured and modelled by the ANEMOC-3 oceanic -blue) and coastal domains with (yellow) and without current effects (red) on the coastal domain at Westhinder buoy over February 2014.

The overestimation given by the oceanic domain can be confirmed by the scatter plots presented in figure 9. An overall improvement is found from the oceanic to the coastal domain with a decrease of the bias from 0.08 m to 0.03 m and of the scatter index from 18.9% to 14.7%, and for the most energetic events with the Q-Q plot closer to the ideal result.

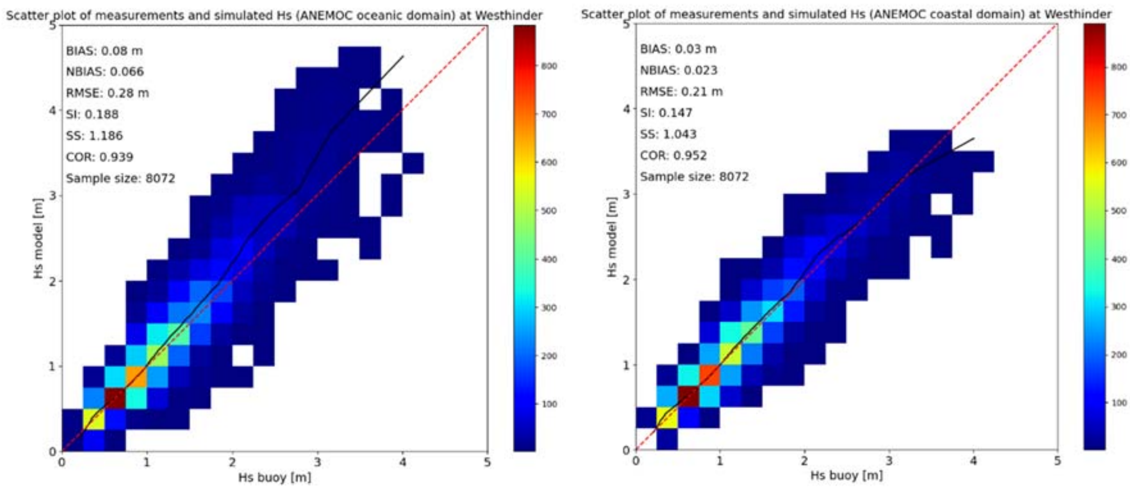

Figure 9. Scatter plot and Q-Q plot of modelled versus measured H_{m0} from the oceanic (left) and coastal (right) ANEMOC-3 domains at Westhinder buoy.

4.2. <u>Altimeter data</u>

As for the altimeter measurements, we used the ESA (European Space Agency) Sea State CCI (Climate Change Initiative) L3 product (PIOLLE *et al.*, 2020). The L3 product contains all the significant wave height measurements that are considered of good quality, merged from the different satellite missions. L3 product is along-track with narrow swath

and resolution of 7 km. The wave parameter we selected for comparison is "swh denoised", which is filtered, adjusted and denoised significant wave height.
We retain the Hs altimeter measurements contained in the subdomain shown in figure 10 covering the Bay of Biscay and the part of Atlantic Ocean up to 12°W. For each Hs altimeter value available, we associated the computed H_{m0} from ANEMOC-3 at nearest node of the model and the same time instant.

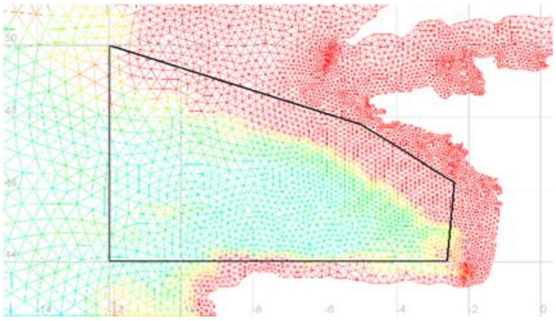

Figure 10. Area (delineated with black solid line) over which ANEMOC-3 and satellite altimeter data are compared over the 6-month period.

The scatter plot and associated Q-Q plot of measured and modelled significant wave height calculated with the oceanic model domain are presented in figure 11. There is a small dispersion of results and the calculated statistical errors are quite low with a SI of 10.4%. Nevertheless, the largest events (i.e. H_{mo} > 12 m) appear to be in general overestimated by the model, which may deserve some refined calibration of the model for better representing these most intense meteorological conditions.

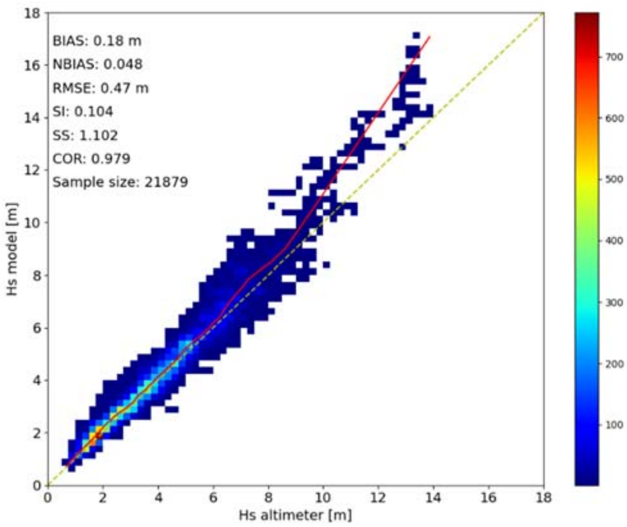

Figure 11. Scatter plot of modelled versus measured H_{m0} from the ANEMOC-3 oceanic domain over the 6-month period for all satellite altimeter measurements included in the subdomain shown in figure 10.

5. Concluding remarks and outlook

The wave numerical hindcast ANEMOC-3, built using the TOMAWAC spectral wave model for wave generation and propagation and the hydrodynamic circulation model TELEMAC-2D for tidal water levels and currents calculation, is being extended to cover the period 1979-2021 (43 years). In the course of the calibration of the database an in-depth analysis and comparisons of results during the energetic events of 2013-2014 winter season was performed. Different *in situ* buoy measurements and altimeter data were compared with numerical results showing an overall good agreement of wave parameters calculated by ANEMOC-3.

Calculated statistical errors confirm this good fit, with extreme events being however often slightly overestimated by the oceanic model domain, and sometimes slightly underestimated by the coastal model domain. The improvements of simulation results brought by the refined grid of the coastal model on one hand, and by the inclusion of the effects due to tidal currents on the other hand have been clearly observed.

From this first series of comparisons, different axes of research are identified, such as (i) testing alternative parameterizations of the physical sink and sources processes in the wave model, (ii) examining other atmospheric reanalyses, such as ERA-5 from the European Centre for Medium-Range Forecasts (ECMWF), (iii) doing refined comparisons with data, in particular by examining the full frequency and directional spectra available at some buoy locations.

6. References

BENOIT M., MARCOS F., BECQ F. (1996). *Development of a third generation shallow-water wave model with unstructured spatial meshing*. In Proc. 25th Int. Conf. on Coastal Eng. (ICCE'1996), 2-6 September 1996, Orlando (FL, USA), pp. 465-478. https://doi.org/10.9753/icce.v25.%25p

BENOIT M., LAFON F. (2004). *A nearshore wave atlas along the coasts of France based on the numerical modelling of wave climate over 25 years*. In Proc. 29th Int. Conf. on Coastal Eng. (ICCE'2004), 19-24 September 2004, Lisbon (Portugal), pp. 714-726. https://doi.org/10.1142/9789812701916_0057

BENOIT M., LAFON F., GOASGUEN G. (2008). *Constitution et exploitation d'une base de données d'états de mer le long des côtes françaises par simulation numérique sur 23 ans. Base ANEMOC en Atlantique – Manche – Mer du Nord*. European Journal of Environmental and Civil Engineering, Vol. 12/1-2, pp. 35-50. http://dx.doi.org/10.1080/19648189.2008.9692994

BOUWS E., KOMEN G. (1983) *On the balance between growth and dissipation in an extreme depth-limited wind-sea in the southern North Sea*. Journal of Physical Oceanography, Vol. 13, pp. 1653-1658. https://doi.org/10.1175/1520-0485(1983)013<1653:OTBBGA>2.0.CO;2

FLATHER R. DAVIES A. (1975). *The application of numerical models to storm surge* *prediction*. Report n°16, Institute of Oceanography Sciences, Cheshire, UK.

HASSELMANN S., HASSELMANN K. (1985). *Computations and parameterizations of the nonlinear energy transfer in gravity-wave spectrum. Part I: a new method for efficient computations of the exact nonlinear transfer integral*. Journal of Physical Oceanography, Vol. 15, pp. 1369–1377. http://dx.doi.org/10.1175/1520- 0485(1985)015<1369:CAPOTN>2.0.CO;2

JANSSEN P. (1989) *Wave induced stress and the drag of air ow sea waves*. Journal of Physical Oceanography, Vol. 19, pp. 745-754. http://dx.doi.org/10.1175/1520-0485(1989)019<0745:WISATD>2.0.CO;2

JANSSEN P. (1991) *Quasi-linear theory of wind-wave generation applied to wave forecasting*. Journal of Physical Oceanography, Vol 21, pp. 1631-1642. http://dx.doi.org/10.1175/1520-0485(1991)021<1631:QLTOWW>2.0.CO;2

KOMEN G.J., HASSELMANN S., HASSELMANN K. (1984). *On the existence of a fully developed wind-sea spectrum*. Journal of Physical Oceanography, Vol. 14, pp 1271–1285. http://dx.doi.org/10.1175/1520-0485(1984)014<1271:OTEOAF>2.0.CO;2

LAFON F., BENOIT M. (2006). *Estimation of extreme wave conditions from hindcast simulations with application to the wave climate along French coasts*. In. Proc. 30th Int. Conf. on Coastal Eng. (ICCE'2006), 3-8 September 2006, San Diego (CA, USA), pp 739-751. https://doi.org/10.1142/9789812709554_0063

LAUGEL A., TIBERY-WADIER A.-L., BENOIT M., MATTAROLO G. (2014) *ANEMOC-2 Atlantique et Méditerranée : calibration et validation de deux nouvelles bases d'états de mer construites par simulations numériques rétrospectives sur 1979-2010.* In Actes des XIIIème Journées Nationales Génie Côtier-Génie Civil, Dunkerque, France, pp. 109-120. doi:10.5150/jngcgc.2014.013

PIOLLE J.-F., DODET G., QUILFEN Y. (2020). *ESA Sea State Climate Change Initiative (Sea_State_cci): Global remote sensing daily merged multi-mission along-track significant wave height, L3 product, version 1.1*. Centre for Environmental Data Analysis, 30 January 2020, http://dx.doi.org/10.5285/3ef6a5a66e9947d39b356251909dc12b

RAOULT C., JOLY A., ANDREEVSKY M., JOLY-LAUGEL A. (2018). *ANEMOC-3: Improving the ANEMOC-2 Sea state database by adding tide effects.* In Actes des 16èmes Journées de l'Hydrodynamique, 27-29 Novembre 2018, Marseille, France.

THORNTON E, GUZA R. (1983). *Transformation of wave height distribution*. Journal of Geophysical Research, Vol. 88, pp. 5925-5938. http://dx.doi.org/10.1029/JC088iC10p05925

VAN DER WESTHUYSEN A. (2012). *Spectral modeling of wave dissipation on negative current gradients*. Coastal Engineering, Vol. 58, pp 17-30. https://doi.org/10.1016/j.coastaleng.2012.05.001