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A 40 YEARS HINDCAST OF WIND, SEA LEVEL AND WAVES IN EUROPEAN WATERS

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ABSTRACT

The paper describes the initial efforts in a project whose objective is to obtain a 40-year hindcast of wind, sea level and wave climatology for European waters. The 40-year global atmospheric re-analysis carried out by the National Centre for Environmental Prediction, Washington, USA (NCEP) and the National Centre for Atmospheric Research, Boulder, Colorado, USA (NCAR) will be used as forcing of limited area atmospheric models. The fine grid atmospheric fields will be used to force state-of-the-art wave models (WAM) and sea level models (HAMSOM and TELEMAC) in regional areas around Europe so as to produce climatic information on waves, sea levels, and currents in a very large extend of the European waters, including the Mediterranean, North East Atlantic and North Sea. The available satellite data, including wind, wave and sea-level data, will be collected and will be used to be compared with the hindcast results, so as to yield uncertainty measures related to the data. Statistical analysis of the produced atmospheric, sea level and wave hindcast and remote sensed data will be performed in order to provide information about the climatological trends in the European Waters and Coastal Seas.

1. INTRODUCTION

The quality of numerical wave and surge hindcasts for offshore and coastal areas depends to a large extend on the quality and the accuracy of the upper boundary conditions, i.e. in particular on the quality of the driving the wind fields. Independent studies have shown that the uncertainty in wind fields has a large impact on the predicted wave fields [1,2].

It has been argued that wave heights approximately scale with the square of the wind speed and this implies that an error of about 10% in the driving wind fields will result in an error of at least 20% in the hindcast wave height [3]. Over the last few years a number of wave and surge reconstructions over the past decades have been performed. One of the more prominent attempts has been provided by the WASA Group [4] in order to verify hypotheses of a worsening wind and wave climate in the Northeast North Atlantic. The wind and wave data set generated by this group has proven to be extremely useful, often being the only source of information available for wave climate and impact studies. For coastal applications, however, this data set still has some limitations. In particular, the wind data, which were used to produce the wave hindcast, suffered from some inhomogeneities along the reconstruction period such as changes in the analysis system or the migration from manual to automatic analyses [5]. In addition, considering coastal applications the spatial and temporal resolution of the provided wind and wave data is relatively coarse. For example, for the wave hindcast the spatial resolution is about $0.5° \times 0.75°$ and the data were stored every 6 hours.

The inhomogeneity problem may now in principle be reduced since atmospheric data for several decades have become available recently from the global reanalysis projects [6,7]. In these projects existing atmospheric data were reanalyzed back in time using a state-of-the-art global atmosphere circulation model together with a frozen state-of-the-art data assimilation system. Additionally, data, which have not been available in real time, are taken into account for the reanalysis and contribute to an enhanced observational database. As a result these reanalysis products can be expected to be much more homogeneous than other gridded atmospheric data sets available so far.

For coastal applications the spatial and temporal resolution of the reanalyzes is, however, still relatively coarse. Presently the global reanalysis have typical spatial resolutions of about 200 km and the data are stored every 6 hours.

To improve on this situation, the project "Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe (HIPOCAS)" was initiated, aiming at generating high-resolution homogeneous 40-year wave and sea level hindcasts with horizontal resolutions that are adequate to represent at least the major features of the coastline and the bathymetry (i.e. about 5-10 km depending on the area), and temporal resolutions between 1 and 3 hours (see tables 1 to 4 in section 3).

The available satellite data, including wind, wave and sea-level data, will be collected as described in [8] and will be used to be compared with the hindcast results, so as to yield uncertainty measures related to the data.

Statistical analysis of the produced atmospheric, sea level and wave hindcast and remote sensed data will be performed in order to provide information about the climatological trends in the European Waters and Coastal Seas. An important feature of this hindcast is that the use of the same numerical models for the whole period will reduce inhomogeneities to a minimum. The length of the period (40 years) allows to carry out reliable statistical analysis from the hindcast data, and the further reduced inhomogeneities will make the data set extremely useful for studying climate trends.

2. ATMOSPHERIC HINDCAST

In order to exploit the potential benefits from the improved homogeneity of the atmospheric reanalysis and to provide wind data at a scale appropriate for coastal applications a dynamical downscaling approach is adopted, i.e. a regional atmosphere model (RAM) is driven by global reanalysis data at its lateral boundaries. As a result wind fields are obtained at higher spatial resolution compared to the global reanalysis. These wind fields are expected to represent the regional features in more detail. Furthermore, these wind fields have been stored hourly.

For this study the regional model REMO [9] is used with the data from the global reanalysis of the National Center for Environmental Prediction (NCEP) for the period 1958 – 1998 [6]. The regional model REMO was set-up for different areas, such that its domain covers in principle those European coastal areas for which wave and surge hindcasts will be performed. In addition, a sufficiently large overlap was chosen, such that higher resolution wind fields are also available for areas that are relevant for the generation of swell, which may propagate into the selected coastal seas. In particular, the model set-ups cover the entire North and the entire Mediterranean Sea as well as large parts of the North Atlantic including the Azores and the Canary Islands. The spatial resolution for these simulations was chosen to be about 50 × 50 km. The simulated wind fields have been stored every hour. For the Irish Sea, the spatial resolution was further increased to about 10 × 10 km by nesting a high-resolution version of the regional model HIRLAM [11] into the REMO simulations.

Usually RAM's are driven by boundary conditions imposed at their lateral boundaries only. In this conventional approach the boundary conditions are forced upon the RAM within a sponge zone along the lateral boundaries [11]. In addition the spectral nudging technique suggested by [12] is used here. This technique is based on the view that small scale details are a result of an interplay between the large scale atmospheric flow and smaller scale geographic features such as topography or land-sea distribution [13]. In addition to the conventional approach, in this analysis nudging terms are added in the spectral domain. These terms have maximum efficiency for large scales and no effect for small scales. Furthermore, their efficiency varies with height and the variable under consideration. For example, there was no nudging for any variable for heights below the 850 hPa level.

In the following, a few preliminary results of this dynamical downscaling exercise for wind fields over European Coastal areas are presented. Figure 1 shows some examples of modeled and observed wind speed at a number of different locations in the North Sea for a period of about one and a half month in February and March 1993. In general, the agreement between the hindcast and the observed wind speed appears to be reasonable for all stations. A comparison with other available products such as those used in [4, 5] is currently processed.

A more detailed comparison for the conditions at the oil platform Ekofisk (56.5° N, 3.2° E) is presented in [12]. They compared wind speeds and directions for a three month period in 1993 obtained from two simulations using either the spectral nudging or the conventional approach with observations. In general, they again found a reasonable agreement between hindcast and observed wind fields. Additionally, they showed that for some events, especially for high wind speeds, the spectral nudging approach performed remarkably better.

In order to assess the quality of the hindcast wind field for the entire reconstruction period the calibration-refinement factorization [14] of the joint probability distribution of observed and modeled wind speed at the station K13-Alpha (53.2° N, 3.2° E) has been computed. The calibration-refinement factorization involves the conditional distribution of the observations x given the hindcast f and the marginal distribution of the hindcast

$$p(f, x) = p(x \mid f) p(f) .$$

The conditional distribution $p(x \mid f)$ indicates how often different observations have occurred when a particular hindcast value was issued. The hindcast is said to be calibrated or reliable if the expectation E of the observations for a given hindcast is the hindcast itself [14]

$$E(x \mid f) = f.$$

Figure 2 shows that in general the wind speed hindcast at K13-Alpha appears to be calibrated and reliable for the period January 1978 until February 1997 (the period for which observations where available). It can be seen further, that the hindcast has a tendency to overestimate wind speeds smaller than about 10 ms^{-1}. For wind speeds larger than about 22 ms^{-1} a slight tendency to underestimate the observed wind speeds can be inferred. However, the number of observations in this range is relatively small (lower panel of Figure 2) and it is difficult to assess whether this represents a real or a sampling problem.

3. WAVE HINDCAST

The availability of high resolution and homogeneous wind data sets as the ones described above allows running wave generation models for the hindcast period to produce, in turn, homogeneous wave data sets for the areas covered by the atmospheric hindcast.

The present project is focused on providing high resolutions in coastal areas where there is the need to model both the coastline and the continental platform. Hourly wave data with a resolution equal or higher than 0.25 degrees is needed. The necessary tradeoff between computing time, coverage and resolution led to a restriction in the number of high resolution areas to be hindcast (see Figure 3). Anyhow, boundary conditions (wave spectra) have to be provided to these areas, so the coverage of the wave models cannot be restricted to the areas shown in the figure. Therefore, the wave grids have been extended to most of the North Atlantic Ocean and the Western Basin of the Mediterranean Sea, although at lower resolutions.

Table 1. Two-way WAM nested application for the North Atlantic Ocean

Grids	North	South	East	West	Grid spacing
Coarse 1	80°	0°	20°	-78°	2° lat. and lon.
Coarse 2	72°	20°	18°	-50°	1° lat. and lon.
Coarse 3	48°	24°	0°	-33°	0.5° lat. and lon.
Coarse 4	60°	49°	0°	-16°	0.5° lat. and lon.
Coarse 5	70°	58°	17°	1°	0.5° lat. and lon.
Fine 1	45°	35°	-1°	-11°	0.25 lat. and lon.
Fine 2	30°	27°	-12.5°	-19°	0.25 lat. and lon.
Fine 3	40°	36°	-24°	-31°	0.25 lat. and lon.

The WAM model [15] is probably the most generalized and tested wave prediction model, used both for hindcasting and forecasting purposes. The cycle 4 of this model [16] has been selected to carry out the HIPOCAS wave hindcast. To obtain the necessary high resolution needed to model the studied areas (see Figure 3) one-way nesting and two-way nesting [17] techniques are employed and 4 sets of applications have been developed to carry out the hindcast. Tables 1 to 4 describe the main features of the 4 grid sets developed for the project. Hourly wind fields (U_{10}) provided by the different atmospheric hindcasts described above provide the forcing for the WAM model.

Table 2. One-way WAM nested application for the North Sea

Grids	North	South	East	West	Grid spacing
Coarse	77.0	38.0	45.0	30.0	0.75 lon, 0.50 lat
Fine 2	56.0	51.0	10.5	3.0	0.10 lon, 0.05 lat

Table 3. Two-way WAM nested application for the Irish Sea

Grids	North	South	East	West	Grid spacing
Coarse 1	58.0	48.0	0.0	15.0	0.5 lat and lon
Coarse 2	57.0	50.0	-2.0	13.0	1/6 lat and lon
Fine	56.0	51.0	-2.5	11.0	1/12 lat and lon

Table 4. Two-way WAM nested application for the Western Basin of the Mediterranean Sea

Grids	North	South	East	West	Grid spacing
Coarse	45.0	34.0	15.0	7.0	0.250 lat and lon
Fine	44.5	34.5	6.5	6.5	0.125 lat and lon

In the North Sea, non-stationary depths provided by an ocean circulation model, will be taken into account.

Measurements are only available for the last decades of the hindcast. Being homogeneous the atmospheric forcing, it can be assumed that the quality derived from the verification of these last years can be extrapolated to the whole period. For this purpose, an effort to compile reliable wave measurements has been carried out and preliminary hindcasts are being carried out. Also, extensive verifications in open waters with the available satellite data [8] will be carried out.

Figure 4 shows preliminary results from the North Sea hindcast at station K13-Alpha (53.2° N, 3.2° E). There is good agreement between modeled and measured data, both in scalar data and directional data. Verifications carried out for the Mediterranean Sea show promising results, although some problems have been detected which need to be solved, for waves generated by offshore winds, being this problem related with the impact of the surrounding orography on the wind fields.

4. SEA LEVEL HINDCAST

Sea level evolution during storm surge events is an important variable by itself in all kind of studies, from harbor design to coastal dynamics. Additionally, water level variations are important for wave evolution when finite depth effects are present. Therefore, a 40-year numerical integration of sea level fluctuations will also be performed. The idea is to study the evolution of the short-term sea level variations (storm surge), as opposed to studying the climatic trends in sea surface elevation, which depend very much from factors (global ocean circulation) that are beyond the scope of this project. Therefore, the core of the work is performed with 2-D barotropic models, which are the tools used by the operational agencies to forecast these phenomena.

Sea level modeling will cover the same areas as wave modeling. The pressure and wind fields used as input for the sea level models will be the results from the atmospheric models described in section 2. Tidal forcing will be introduced at the model by imposing tidal elevation at the open boundaries.

4.1 North Sea

Integration will be done using the finite element TELEMAC2D code. Bathymetry data used in the forecast model from the Federal Maritime and Hydrographic Agency of Germany (BSH) were the basis for North Sea Model bathymetry. The model domain covers the North Sea south of 59º N. The model consists of 27,000 nodes and approximately 50,000 triangular elements with a vortex length varying between 75 meters and 27 kilometers. The boundary conditions towards the open-flow boundary (Atlantic Ocean) were generated using 13 harmonic constants from BSH [18].

The influence of Atlantic external surges is important for a precise calculation of the water elevation in the North-Sea model domain. It is well known that external surges propagate counterclockwise towards the North Sea like a monochromatic Kelvin-wave [19]. In order to take this phenomena into account, the measured time series of the water elevation at the tide-gauge Aberdeen are used to calculate the external-surges as the difference between the measurement and a synthetic astronomical water elevation. After smoothing the noisy external-surge by a Fast-Fourier-Transformation this gives an auxiliary water elevation added to the prescribed water level at the open boundaries (Wick/Stavanger). Sometimes the amplitudes of external-surges reach more than 50 cm height during a period of 1-3 days.

4.2 Atlantic Coast and Mediterranean Sea

The integration for both areas will be done by means of the HAMSOM model [20-23; 25]. This model is a three-dimensional multi-level (z coordinate) finite difference model (Arakawa C grid) based on the baroclinic set of Reynolds equations. It is being used barotropic and vertically integrated in these studies.

In both areas the resolution will be 15'x10' and time-step 10 minutes. The model will be forced by winds and atmospheric pressures generated by the HIPOCAS REMO applications for the Eastern North-Atlantic and Mediterranean respectively.

Tidal constants for the Eastern North-Atlantic area will be obtained by means of interpolation of the newest version data set bay Ray [24].

The modeling of sea level residuals is of particular interest in the Mediterranean Sea, since the tide amplitude is very low and the response of the sea to the atmospheric forcing is the dominant signal. The very low tidal range allows an independent model computation of residuals and tides, since non-linear energy transfer between tides and surges are very low [25]. Therefore, sea level response is computed without tide forcing, a periodic signal that can be added in the post-processing.

Due to this very low tidal forcing the computation of atmospheric residuals is very important in this basin because in most of the recorded signal does have this origin. The use of a numerical model is necessary for this task, because the inverse barometer correction can not be directly applied [26] and the effect of the wind must be taken into account during storm events, although the contribution of this last forcing is smaller than in other areas (like the North Sea) due to the much narrower shelf generally present.

The model domain covers the whole Mediterranean Sea (see figure 5). For one day simulation the model needs 15 minutes of cpu time using 4 processors of a SPP-2000 computer.

At this stage all the bathymetry data sets are implemented, the model set-up are finished and the first results of the sea–level models are being available for validation purposes. Model results will be validated with measurements from tide gauge stations in all the areas. Statistics will be made computing the classical parameters: correlation index, root mean square error, etc. Figure 6 shows the results of one of this initial validation tests. The figure corresponds to the Valencia harbor and the simulation was done with the Mediterranean Sea application forced with winds and pressures generated by the HIPOCAS Mediterranean application of the REMO model.

5. SYNTHESIS OF RESULTS

The use of more than one type of data is important for validation and to increase the amount of available data for statistics, as discussed for example in Guedes Soares [27].

Altimeter data from ERS1, ERS2 and Topex-Poseidon will be sorted in order to organize the available remote sensed data including wind, wave, sea-level, storm surge and ice-sea measurements for same areas for which hindcasts are being made, as described in [8].

Whenever the hindcast and remote sensed data are available they will be compared in order to assess the level of uncertainty involved in using the different type of data.

Statistical analysis of the produced atmospheric, circulation, waves and remote sensed data will be performed in order to provide information about the climatological trends in the European Waters and Coastal Seas.

Finally, an atlas will be produced with the obtained wind, wave and current climatology for the European Waters and Coastal Seas.

6. CONCLUSIONS

An approach was presented to produce homogeneous, high-resolution wind hindcasts for the past four decades for coastal applications. The approach is based on driving a regional atmospheric model with the NCEP reanalysis for the past 40 years. The wind fields generated this way will be available hourly at a spatial resolution of about 50 km for the North Sea, the Mediterranean Sea, and parts of the North Atlantic including the Azores and the Canary Islands. For the Irish Sea wind fields at a horizontal resolution of about 10 km will be provided. For the North Sea the wind fields are readily available for the entire reconstruction period. For all other areas they are currently processed.

Preliminary results suggest that the wind fields produced this way show a good agreement with observations and are reasonable for applications such as wave and surge modeling in coastal areas.

Different set-ups of one-way nested grids and two-way nested grids have been developed and will be used to hindcast the period in order to produce hourly, high resolution, wave data sets. The forcing is provided by the atmospheric hindcast presented in the previous section. Preliminary results suggest that the wave data produced this way show a good agreement with observations, although problems found in waves related with offshore winds needs further investigation.

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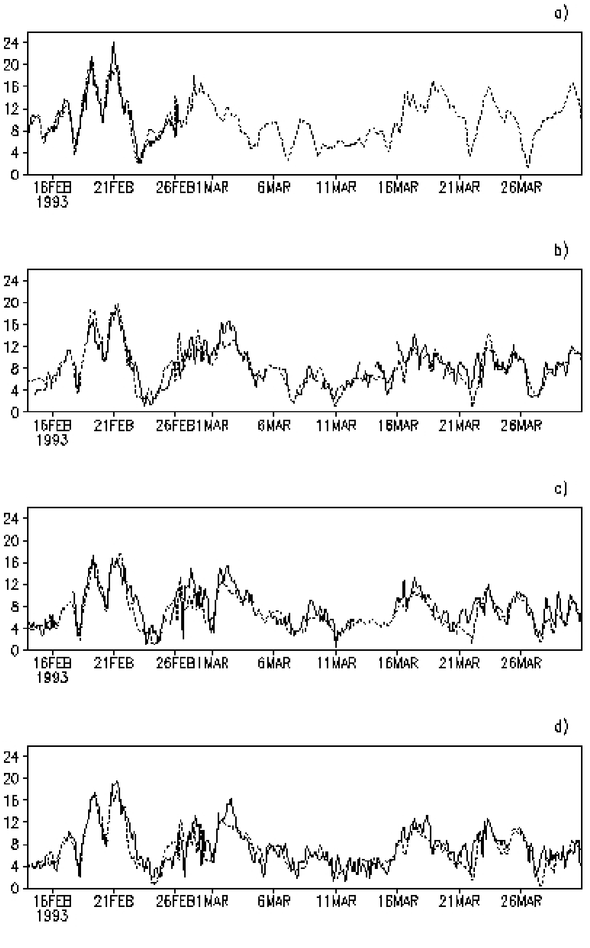

Figure 1. Comparison of modeled (dashed) and observed (solid) wind speed at (a) AUK (56.4° N, 2.1° E), (b) K13-Alpha (53.2° N, 3.2° E), (c) EUR (52.0° N, 3.3° E), and (d) YM6 (52.6° N, 4.1° E) for the period 14 February 1993 until 31 March 1993.

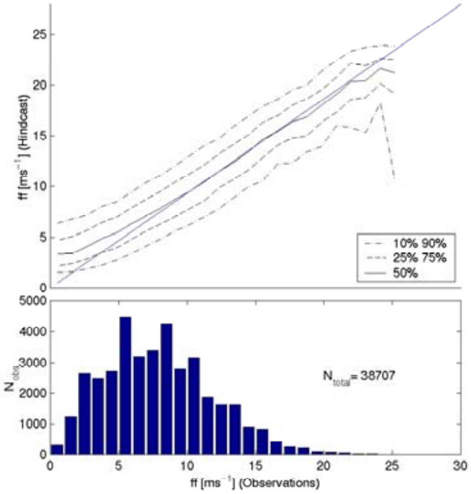

Figure 2. Calibration-refinement factorization of the joint probability distribution of observed and hindcast wind speed for the period January 1978 until February 1997 for the station K-13 Alpha in the Southern North Sea. The abscissa represents observed, the ordinate the hindcast wind speed. The two solid lines show the expectation value and the line $y = x$. The dashed lines represent the 10, 25, 75, and 95% Quantiles. The lower panel shows a histogram of wind speed observations.

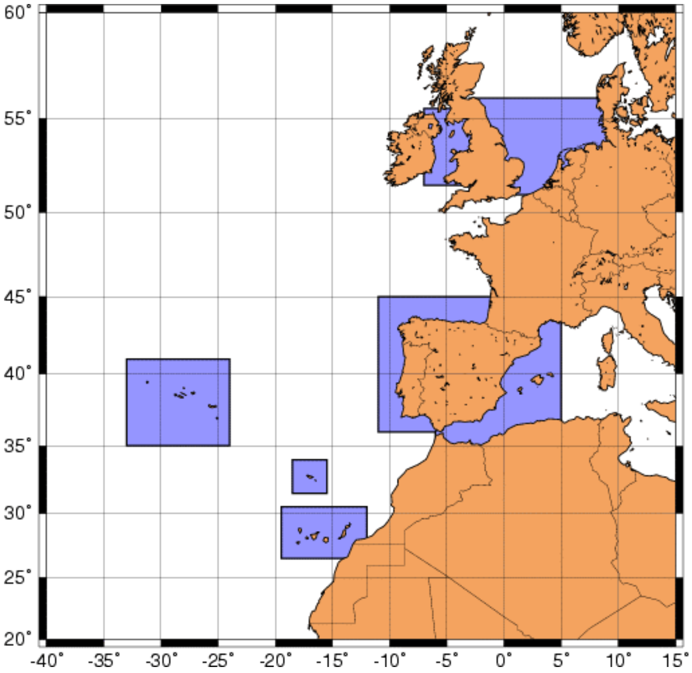

Figure 3. Waves in the areas shown in blue will be hindcasted in detail. The coverage of the different wave grids will allow to produce, by one-way or two-way grid nesting, high resolution boundary conditions for these areas.

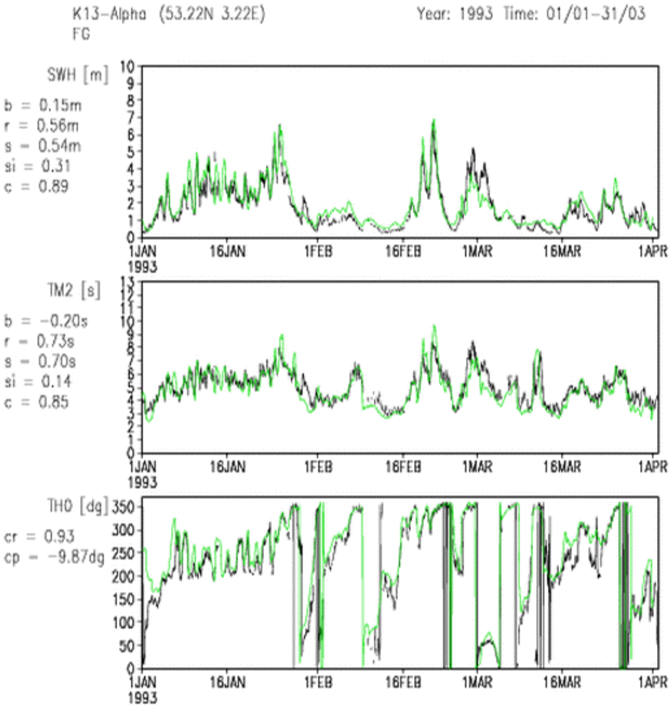

Figure 4. Modelled (solid green line) and measured (solid black line) time series for K13-Alpha station in the North Sea (53.2° N, 3.2° E) for the period January to March 93. Model wave data has been produced by the fine grid application of the WAM model for the North Sea. Statistical parameters for the comparison are also shown at the left side of the figure.

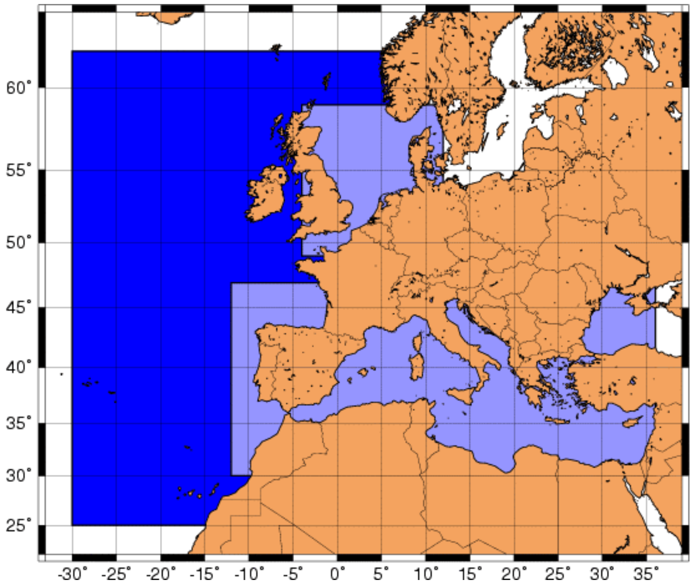

Figure 5. Sea level hindcast model domains (Atlantic, North Sea and Mediterranean Sea. Atlantic application (dark blue) east limit is 6°E.

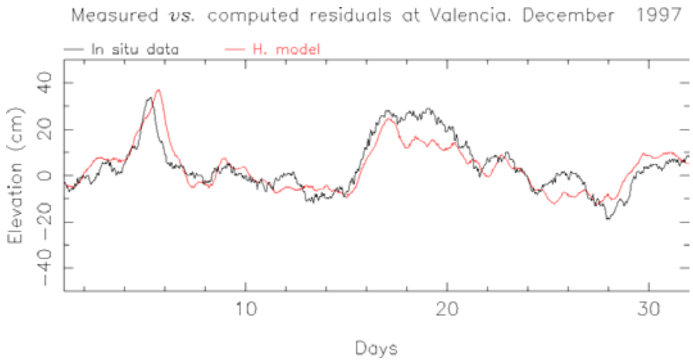

Figure 6. Modelled (solid RED line) and measured (solid black line) time series for residuals at Valencia station in the Mediterranean Sea (53.2° N, 3.2° E) for December 1997. Model wave data has been produced by Mediterranean application of the HAMSOM forced by data generated by the REMO application, both within HIPOCAS.