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On the feasibility of the use of wind SAR to downscale waves on shallow water

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Abstract

On the recent years wave reanalysis have become popular as a powerful source of information for wave climate research and engineering applications. These wave reanalysis provide continuous time-series of offshore wave parameters, nevertheless on coastal areas or shallow water waves are poorly described because spatial resolution is not detailed. By means of wave downscaling it is possible to increase spatial resolution in high temporal coverage simulations, using forcing from wind and offshore wave databases. Meanwhile the reanalysis wave databases are enough to describe the wave climate on the limit of simulations, wind reanalysis at an adequate spatial resolution to describe the wind structure near the coast are not frequently available. Remote Sensing Synthetic Aperture Radar (SAR) has the ability to detect sea surface signatures and estimate wind field at high resolution (up to 300 m) and high frequency.

In this work a wave downscaling is done on the northern Adriatic sea, using an hybrid methodology and Global wave and wind reanalysis as forcing. The wave fields produced were compared to wave fields produced with SAR winds that represent the two dominant wind regimes in the area: the Bora (ENE direction) and Sirocco (SE direction). Results show a good correlation between the waves forced with reanalysis wind and SAR wind. In addition, a validation of reanalysis is shown. This research demonstrates how Earth Observation products, as SAR wind fields, can be successfully up-taken into oceanographic modeling, producing similar downscaled wave field when compared to waves forced with reanalysis wind.

1 Introduction

The synergic use of Earth Observation (EO), wave reanalysis and in situ measurement can be adopted for providing scientific justifications for the appropriate selection of off-shores wind farms location. The Level-2 SAR (Synthetic Aperture Radar) products can help to better understand the wind fields in open-sea areas (Pieralice et al., 2014), while wave reanalysis and in situ monitoring could be integrated and calibrated using the satellite information. The ability to retrieve wind fields from SAR images, taking advantage of the high resolution (sub-kilometer) and wide coverage (500 km) offered by wide swath images represents an important improvement for wave reanalysis applications where knowledge of the wind field is crucial. On the recent years, in fact, wave reanalysis have become popular as a powerful source of information for wave climate research and engineering applications. These wave reanalysis provide continuous time-series of offshore wave parameters, nevertheless on coastal areas or shallow water waves are poorly described because spatial resolution is not detailed (Camus et al., 2013).

2 Study area

The Adriatic Sea is a shallow semi-enclosed shelf sea located between western and eastern parts of the Mediterranean Sea; it is about 800 long and 150 km wide. Northern Adriatic Sea occupy the northern and shallower area (depth < 50 m) and has a gentle slope (about 0.02°). Figure 1 shows the study area and the wind wake patterns from Sigma0 SAR intensity of ENVISAT ASAR WS image acquired on 02 February 2012 20:59:29 UTC, the rectangle indicates the downscaling area and the location of a wave buoy with available data for validation.

The general cyclonic water circulation system of northern Adriatic Sea is highly variable with seasons (Artegiani et al., 1997; Zavatarelli and Pinardi, 2003; Pullen et al., 2003). One of the major features is a coastal current along the western side of the basin, the Western Adriatic Coastal Current (WACC), driven by wind and thermohaline forcing (Poulain, 2001). In northern Adriatic Sea the main forcing of waves are the local winds. Two distinct wind regimes, Bora and Sirocco, dominate conditions in the area and influence basin-wide circulation (Orlić et al., 1994). Bora is a downwelling favorable wind blowing from ENE with a mean speed of 15 $\mathrm{m\,s^{-1}}$, shows an evident interannual variability (Bignami et al., 2007) and can generate large waves with significant wave heights of 1 m, and period of 5 s (Cavaleri et al., 1997). In contrast, Sirocco is an upwelling favorable wind which blows from the southeast with a typical speed of 10 m s^{-1} and brings warm Mediterranean air (Orlić et al., 1994) and generates lower wave height, but longer wave period in order of 10 s in the NAS region (Wang et al., 2007). It has an available fetch of several hundreds of kilometers and is thus particularly efficient in modulating the wave field, more so than Bora, whose fetch is restricted to the narrow width of the Adriatic Sea (Cavaleri et al., 1997; Signell et al., 2005).

Bignami et al. (2007) pointed out that the inhomogeneity in Bora wind speed distribution is not equally represented by the wind products at different spatial resolutions. Atmospherical models do not represent the detailed range of Bora wind spatial variability, like the dual-jet nature of the Trieste jet or the several -kilometer-wavelength structures in the Bakar and Senj jet region. Estimated wind fields at fine scale from SAR satellite allow the observation of morphology, wake patterns, the formation of the barrier jet on the western Adriatic coast and, where present, dual-jet structure of the Bora wind (Signell et al., 2010; Adamo et al., 2013).

3 Materials

3.1 Wind

3.1.1 Wind reanalysis

SEAWIND I reanalysis is a regional dynamical atmospheric downscaling that covers the North Atlantic and Mediterranean regions. Simulations were done using the Weather Research and Forecasting (WRF) model (version 3.1.1) with the Advanced Research dynamical solver (WRF-ARW) (Skamarock et al., 2008). The resolution of modeled wind fields in the reanalysis is defined with 40 vertical hybrid levels (7 first levels below the first 1000 m) and 30 km horizontal resolution. The database spans from 1948 to march 2013. This reanalysis has been validated for sea winds comparing the database with in situ buoys and satellite data. The in situ buoys used in this process comes from REDEXT and REMPOR net of buoys of and meteorological stations from Puertos del Estado (Spanish National Ports and Harbour Authority). Also satellite data from ERS-2 (1995–2003), Envisat (2002), GFO (2000–2008), Jason-1 (2002), Jason-2 (2008) and T*P^{-1} (1992–2005) were used for the validations.

3.1.2 Wind SAR fields

Wind field products have been collected from SOPRANO service, developed by CLS (Collecte Localization Satellites). Envisat ASAR Wide Swath Mode data VV polarized have been processed using SAR2WNF software v.3.0.0. Scattering model used to estimate wind field from Normalized Radar Cross Section (NRCS) is CMOD-IFR2 (Quilfen et al., 1998) for NRCS developed by for VV-polarized C-band scatterometry, using a priori wind direction from ECMWF 33 h wind forecast at 0.25° resolution.

For the retrieval of SAR data archive, in order to investigate the ability of the SAR for the winds and waves productions, the following criteria were used for data collection:

a. collection of all SAR data involving critical events in northern Adriatic basin,

b. selection of SAR data in relation to the existence of ground truth data or obtained from other EO sources (VHR optical satellite data),

c. selection of SAR data based on information provided by weather and sea reanalysis.

A total of 15 high resolution wind fields at 0.01° spatial resolution, estimated from satellite SAR acquired between December 2011 and April 2012 has been used as forcing in wind waves modeling. Figure 2 show the available wind SAR fields to forcing the model. The transport of Stokes, as well as the wind, especially end of January 2012 retained the same direction for many days, increasing in intensity thanks to bora that was blowing in those days.

3.2 Waves

The Global Ocean Waves (GOW) reanalysis is a historical reconstruction of ocean waves. GOW has been generated from the spectral model WaveWatch III (Tolman, 1989, 1997). Spectral wave models a level of accuracy that enables reproducing significant wave height and peak period with errors below 15 %. Wavewatch III is a third generation wave model developed at NOAA-NCEP (Tolman, 2002, 2009). It solves the spectral action density balance equation for wave number direction spectra. The model can generally be applied to large spatial scales and outside the surf zone. Parameterizations of physical processes include wave growth and decay due to the actions of wind, nonlinear resonant interactions, dissipation (whitecapping) and bottom friction. Bathymetry, ice cover and wind forcing, databases are crucial for a good historical hindcast of ocean waves.

GOW encompasses several hourly reanalysis projects at different spatial resolutions: a global wave reanalysis as well as several regional wave reanalysis in Europe and Latin America (Fig. 3). Adequate configured model and input forcing have been used for each project. Detailed information about particular GOW projects can be found in Reguero et al. (2012). In particular, the GOW used in this work (whose domain is identified with the dashed line on Fig. 3) was forced with the CFSR reanalysis and spans from 1979 to present. The grid resolution in the Mediterranean is 0.18° (20 km). This database was validated using satellite and buoys data, finding correlations upper to 0.95 and scatter index lower than 0.15 along the Atlantic coast.

3.3 In situ dataset

In situ data used for validation of downscaled waves were collected from a mooring buoy located at GNL Terminal (yellow mark in Fig. 1), acquiring hourly the following parameters: Wave Height, Wave Direction, Wave Period.

4 Methods

The methodology used in this work is divided in two main parts: in the first part wave downscaling is done, and on the second part, the SAR wind fields are used to force the numerical model. The wave downscaling were done following the hybrid methodology described in Camus et al. (2011a) in which a small number of waves and wind conditions were selected by means of the maximum dissimilitude method, propagated using the SWAN model (Booij et al., 1999), then wave time series were reconstructed using Radial Basis Function interpolation.

Lately, 15 high resolution wind fields, estimated from satellite SAR acquired between December 2011 and April 2012 and corresponding to transient occurrences of main wind regimes with a typical duration of several days, were used for wave downscaling. As results, the wave fields forced with modeled wind fields and with wind SAR fields were compared. The development of the DOW database implies several steps, which are summarized in Fig. 4. The steps of the proposed global framework are: (a) analysis of the reanalysis databases available in the study area (b) calibration of the reanalysis databases in deep water with instrumental data, (c) selection of a limited number of cases which are the most representative of wave and wind hourly conditions in deep water, (d) propagation of the selected cases using a wave propagation model, (e) reconstruction of the time series of sea state parameters at shallow water; (f) validation of the coastal wave data with instrumental data; and (g) characterization of wave climate by means of a statistical technique. This methodology was developed on the IH-Cantabria (Camus et al., 2011a) and have been applied to downscale waves on Spain, Brazil, Oman, etc.

The second part of the work consist on the wave simulation of Bora and Sirocco events observed on the SAR wind fields. This were done using the same domain than in the downscaling and the wave climate on the open boundary. As there are only 15 SAR wind fields, every wind field is treated as a single simulation, and the instantaneous wind field as the mean wind field during a 1 h sea state.

4.1 Wave downscaling

4.1.1 Setting

The methodology described on Fig. 4 was applied to northern Adriatic Sea. As inputs were used the GOW Mediterranean (Reguero et al., 2012) grid (Fig. 3) with a spatial resolution of 0.18° (20 km) and the Seawind I database (Menéndez et al., 2013) with a spatial resolution of 30 km × 30 km (Fig. 1).

The domain is small enough so that wave propagation across the area occurs at a faster rate than the change in offshore forcing at the domain boundary, therefore stationary conditions for wave simulations can be assumed. The dimensions of the downscaling grid (Fig. 1) are 166 × 110 with a resolution of 1 km. The bathymetry of the dynamical downscaling grids is defined by means of the global bathymetry "General Bathymetric Chart of the Oceans" (GEBCO), with a spatial resolution of 1′ from a combination of sounding waves and satellite data, available at the British Data Centre (BDOC).

Wave climate definition for the open boundary of downscaling was obtained from GOW database. The output parameters of GOW are: the significant wave height (H_s), the peak period (T_p), mean wave direction (θm) and the directional energy spectra in the boundaries of the DOW grid. Figure 1 shows the location were the output boundary conditions were obtained.

4.1.2 Calibration

Due to insufficient resolution of forcing wind fields and spatial and temporal model resolutions, a parametric calibration was done following Mínguez et al. (2011). This method corrects significant wave heights with instrumental data from satellite according to the mean wave direction. The model can be shown on Eq. (1).

$$H_\mathrm{s}^\mathrm{C} = a^\mathrm{R}(\theta)\left[H_\mathrm{s}^\mathrm{R}\right]^{b^\mathrm{R}(\theta)} \tag{1}$$

where H_s^R is the reanalysis significant wave height, H_s^C is the calibrated significant wave height and $a^R(\theta)$ and $b^R(\theta)$ are the parameters dependent on the mean wave direction θ from reanalysis. A complete explanation of this methodology can be found on Mínguez et al. (2011).

This correction is applied to each boundary node on the downscaling grid. The pairs of data for the calibration were obtained choosing all the satellite data in a radius of 1.5°.

4.1.3 Selection

The selection is done to obtain a set of representative scenarios of ocean conditions of the total database. Selection is done applying a maximum-dissimilarity algorithm (MDA). The MDA has been proved to identify the most dissimilarity wave conditions on a reanalysis database including the extreme events. The algorithm and details of selection are described on Camus et al. (2011b).

This part of the methodology has three steps: (i) Set wind grid points and wave grid points which define forcing of the numerical propagations. Standardize the calibrated data after the wave and wind directions have been transformed to the x and y components. (ii) Apply the principal component analysis to the standardized forcing. Select the number of principal components i.e. the variables in the new reduced space, which produces an acceptable root-mean-square error reconstruction. (iii) Select a representative number of offshore conditions using the MDA in the reduced space and identify these select cases in the original space.

The forcing conditions are defined by the wave reanalysis nodes along the domain boundary and the simultaneous wind fields. In this way the wave spatial variability and the local wind wave generation is taken into account. The GOW Mediterranean with spatial resolution of 0.18° are used to define the boundaries of the DOW grid, meanwhile the SeaWind I database are used to define the wind fields. Figure 1 shows the dynamical downscaling grid, the GOW and Seawind nodes. The parameters used in the selection process and in time series reconstruction are the hourly series of wave height (H_s), the mean wave period (T_m) and the mean wave direction (θm) of every N nodes at the computation boundaries, and the hourly series of wind directional components of the nodes at the upper boundary of the wind grid.

To avoid highly correlation situations among grid points of a given variable and among different variables a Principal Component Analysis (PCA) is done. The PCA reduces the dimension of the data preserving the maximum variance of the sample data. The selection of the most appropriate number of PCAs is based on the reconstruction root-mean-square-error (RMSE) of the offshore wave and wind conditions. In this case the first 15th PCs explained 99.0 % of the variance of the original database, therefore the dimension of the hourly series were reduced from 35 to 15 with no significant information loss.

The next step consists of selecting a representative subset using MDA. The first element of the selection coincide with the largest significant wave height, identified in the original space. Figure 5 shows the subset of size $M = 100$ elements selected in the EOF space. The selected cases are fairly distributed in the data space. This subset, selected by MDA, is not projected back to the original space. The selected elements are identified in the original series of the wave conditions.

4.1.4 Deep to shallow water transformation

The representative cases, selected by MDA, of wave climate are propagated to coastal areas using the numerical model SWAN (Booij et al., 1999). For each case, on every DOW grid nodes the propagated significant wave height ($H_{\mathrm{s}_{\mathrm{p},j}}$), the peak period ($T_{\mathrm{p}_{\mathrm{p},j}}$) and the mean direction ($\theta \mathrm{m}_{\mathrm{p},j}$) are stored. Therefore the M propagations in DOW domain define a catalog of cases formed by the $M = 100$ hourly sea state parameters corresponding to a certain sea state condition in deep water.

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4.1.5 Time series reconstruction

Finally the reconstruction of the time series of wave parameters on the DOW grid is done by means of a radial basis functions (RBF) interpolation. A detailed description can be found on Camus et al. (2011a).

4.2 Wind satellite simulations

Analysis of SAR wind fields is twofold. First, the SAR wind fields were compared to the modeled wind fields in order to highlight the differences between both wind sources. Second, the SAR wind fields were used to force the numerical model and produce wave fields. These simulations were also forced with the corresponding wave climate through the open boundary.

4.2.1 Wind field comparisons

The comparison between the SAR wind fields and modeled wind fields cannot be done directly due to the different nature of the measurements. The hourly reanalysis wind fields represent the mean conditions of wind (both in magnitude and in direction) during an hour on a coarse grid. On the other hand, the SAR wind database represent the instantaneous wind fields, namely the wind field at the exact moment when the satellite overpasses the area, estimated at high spatial resolution. Therefore, to have an adequate comparison between both wind sources, the SAR wind fields were interpolated to the coarse resolution grid of wind reanalysis and only qualitative comparisons were done.

4.2.2 Wave simulations with SAR wind fields

Simulations were done using the SWAN model, using the same domain that in the previous section and as forcing the SAR wind fields and the corresponding wave fields. These simulations were compared with simulations forced with the SeaWind I reanalysis wind fields. Figure 6 show some examples of the comparisons between the wave fields forced with SAR winds and reanalysis winds.

5 Results and discussion

The principle of wind and waves reconstruction is based on the estimation of suitable parameters that characterize the signal and in the case of the SAR radar and other EO systems. More specifically the ratio signal/clutter with clutter where is a set of interference signals that do not can be traced back to the target and that generally worsen the contrast between target and background of the target and highlight the SAR wind data. It was found a high similarity between the SAR wind field and the reanalysis wind field, this suggests that there is a high persistence of wind direction during a time step of one hour (Fig. 7). Although there are cases where wind sources show opposite directions, due to low resolution of the modeled winds, a good correlation was found on the downscaled waves.

Thus the estimation of wind fields obtained by means of a Bayesian approach, exploits both the radar cross-section of the normalized SAR and external information, such as the fields of wind meteorological models (Numerical Weather Product). Results show that although SAR wind fields were able to solve fine scale spatial patterns and improve wave downscaling in the study area, especially during Bora wind events due to complex orography in the Istrian coast, the following weaknesses were found:

- the domain is not always fully covered by satellite acquisitions, even using wide swath acquisition modes;
- the estimated wind fields represent the instantaneous conditions of winds, and not the mean condition during one hour (requirement for wave downscaling);
- temporal resolution is limited (1 observation every 3–16 days), while typically hourly data are required for wave downscaling.

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To solve temporal resolution issue, the use of blended wind product from either SAR wind or modeled wind may represents a solution to supply SWAN model with consistent wind forcing, as successfully demonstrated in Benassai et al. (2015).

As validation of propagated waves, a series of wave height was reconstructed on the buoy location and compared with in situ measurements. Figure 8 shows a 6 month segment (winter 2011 to spring 2012) of both observed and modeled wave height series. During this period the correlation between reanalysis and data buoy is of 87 % being the simulation able to reproduce events of high and low wave height events. On the same figure blue dots indicate the wave height obtained using the SAR wind fields as forcing. It can be observed that SAR wind simulations depict the same behaviour of time series although some of these correspond to periods of small waves or relative calms.

Figure 9 shows scatter and quantile-quantile (20 equally distributed Gumbel quantiles) plots of the measured vs. modeled H_s, for the entire dataset of buoy indicating the general good quality of the results obtained. Several diagnosis statistics are calculated to compare model performance with respect to instrumental data, such as the root mean square error (RMSE), the Pearson's correlations coefficient (ρ), the systematic deviation between two random variables (BIAS) and the residual scatter index (SI). Finally, Fig. 10 incorporate on the scatterplot the downscaled wave heights simulated using SAR wind (red points) and the modeled wind (green points). In general both simulations of the sea states, where SAR winds were available, describe statistically equivalent results for the wave height, although for larger waves modeled winds produce larger waves than SAR winds. Nevertheless, there are not enough intense wind stress cases to find a statistically robust trend.

In comparison with previous experimental research (Camus et al., 2011a), results carried out from this work show the ability of SAR satellite data to force time series of wave fields by means of a radial basis functions (RBF) interpolation. Considering previous attempts to force wave simulations using SAR wind (Benassai et al., 2013, 2015), advancement was reached using an efficient methodology to downscale waves on shallow water in mid term simulations (days to months).

6 Conclusions

A wave climate downscaling of northern Adriatic Sea was done applying the methodology described on Camus et al. (2011a). The downscaling was forced with a regional wind reanalysis (SeaWind I) and a global reanalysis of waves (GOW Mediterranean). The downscaling was done using a hybrid methodology that consist on the selection of a set of wave climate cases by means of the maximum dissimilitude technique, the propagation of these cases, and finally the reconstruction of time series by means of radial basis functions. Several SAR wind fields were analyzed and used to force the model to propagate the wind waves on the downscaled area.

Comparison with in situ instrumental data indicate the general good quality of the downscaled waves. Although there are differences between SAR and modeled wind fields, a good correlation was found on the downscaled waves forced with different wind fields.

This research demonstrates how EO products, as SAR wind fields, can be successfully up-taken into oceanographic modeling, as if by reconstructing time series of wave fields using radial basis functions (RBF) interpolation. Operational SENTINEL-1 will produce a consistent long-term data archive (Level-2 – Ocean) built for these applications based on long time series, opening the way for new improvements on services for operational oceanography.

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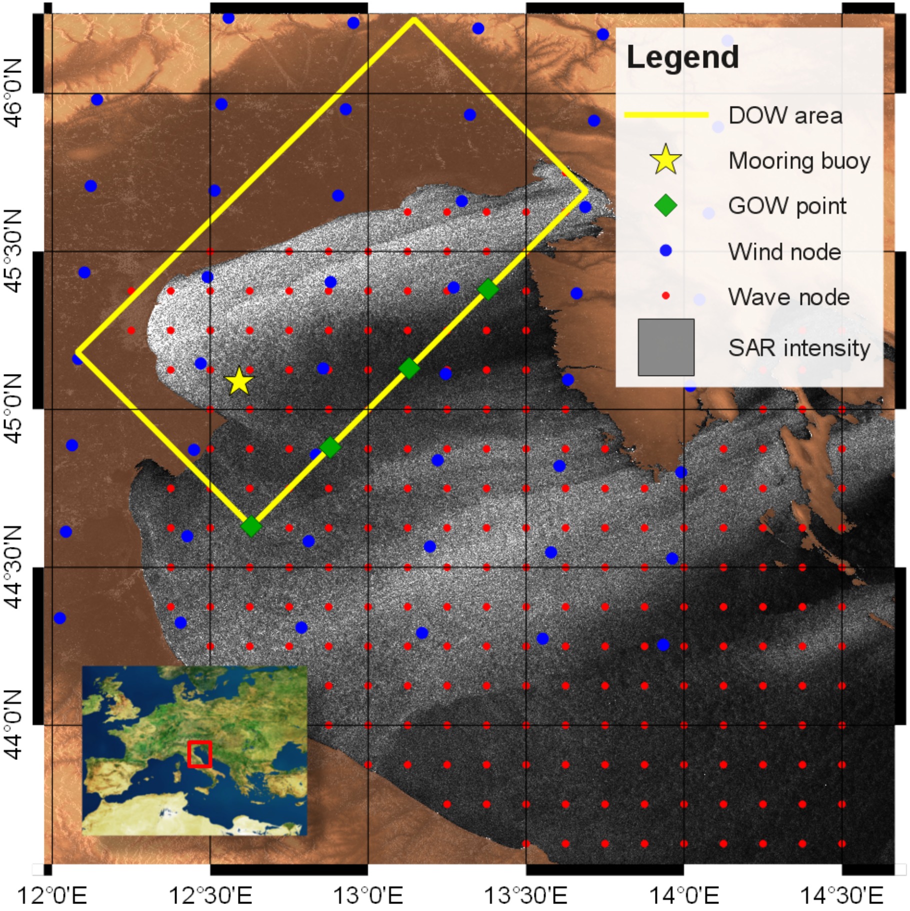

Figure 1. Modeled domain in northern Adriatic Sea basin. Background shows Sigma0 of ENVISAT ASAR WS image acquired on 02 February 2012 20:59:29 UTC.

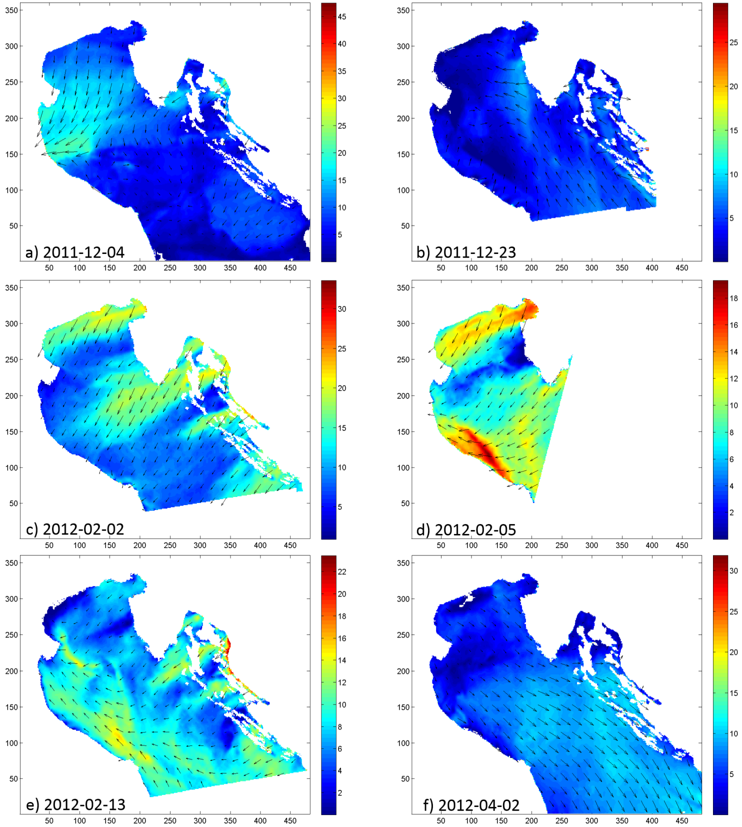

Figure 2. Some of the 15 SAR wind fields available for wave simulation.

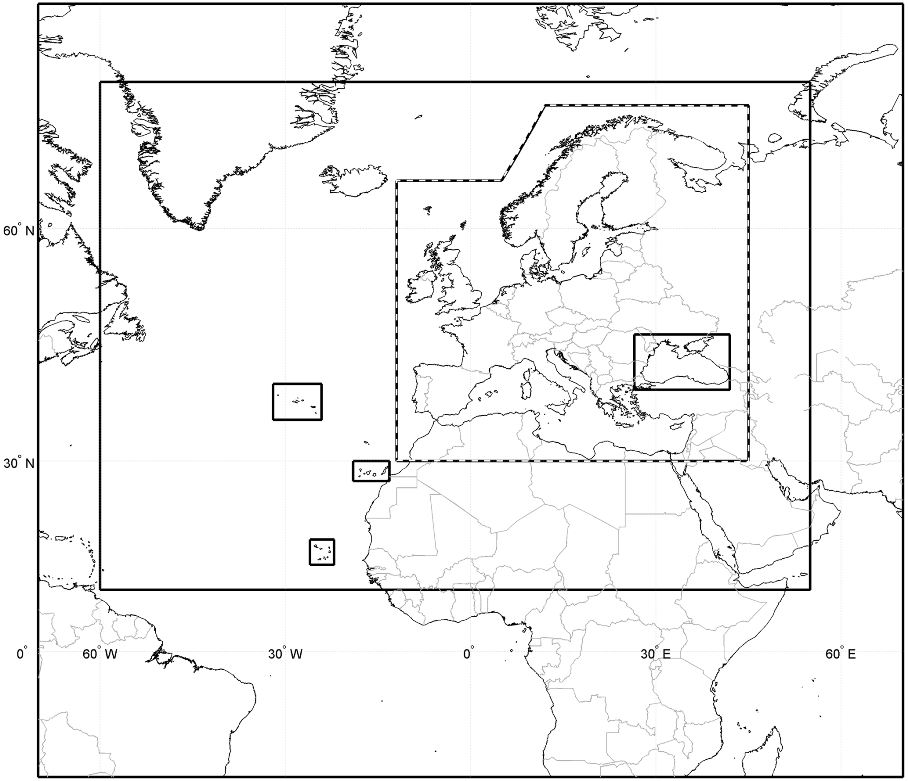

Figure 3. Wave reanalysis domains in Europe.

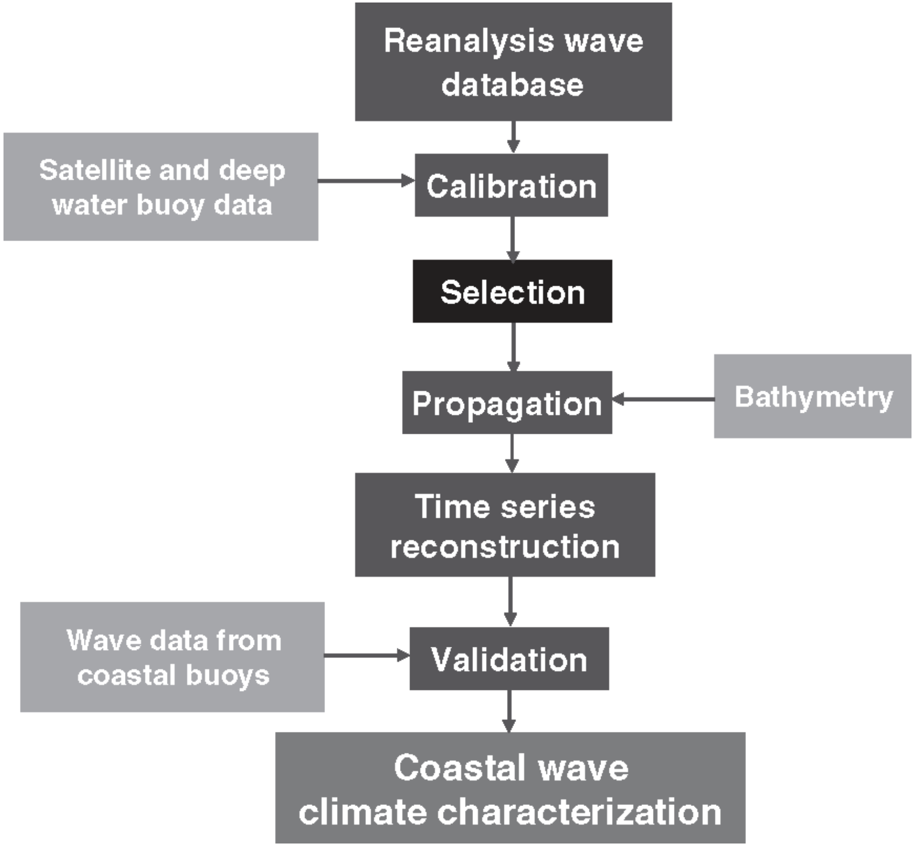

Figure 4. Methodology to downscale wave climate to coastal areas.

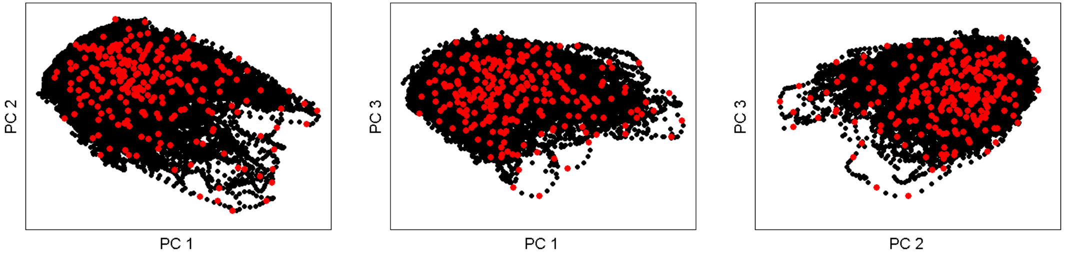

Figure 5. Subset of selected cases.

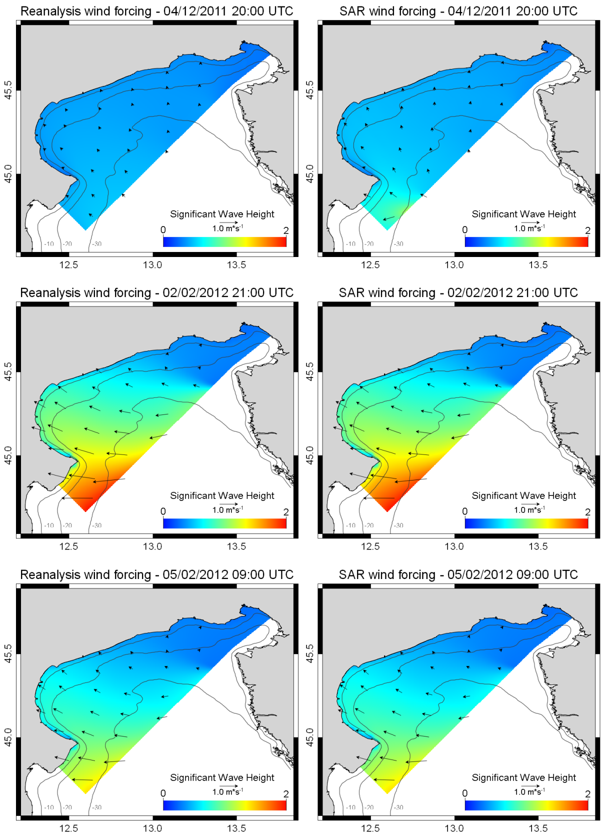

Figure 6. Some cases of waves fields forced with Reanalysis winds (left) and SAR winds (right). Solid isolines are the bathymetric contour lines.

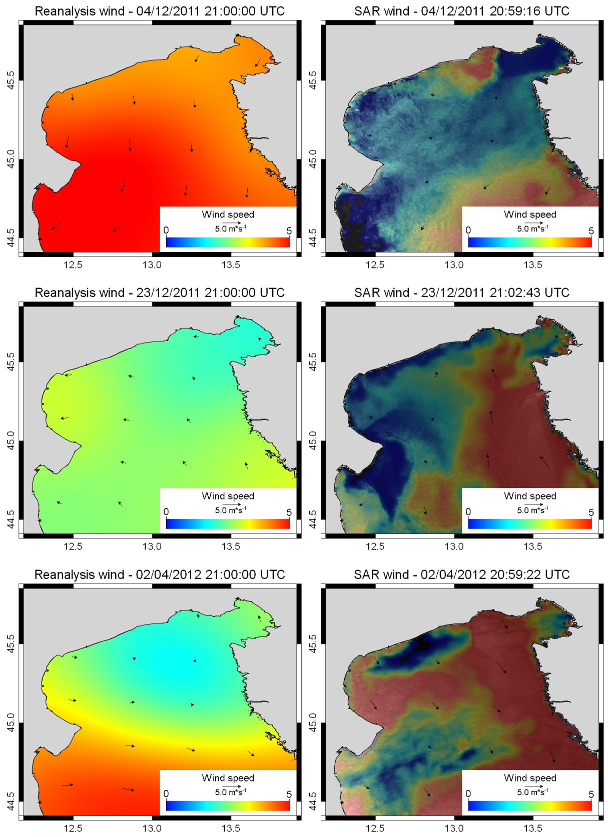

Figure 7. Examples of wind fields with similar patterns between SAR and Reanalysis. SAR winds fields (right) are superimposed to correspondent Sigma0 SAR intensity.

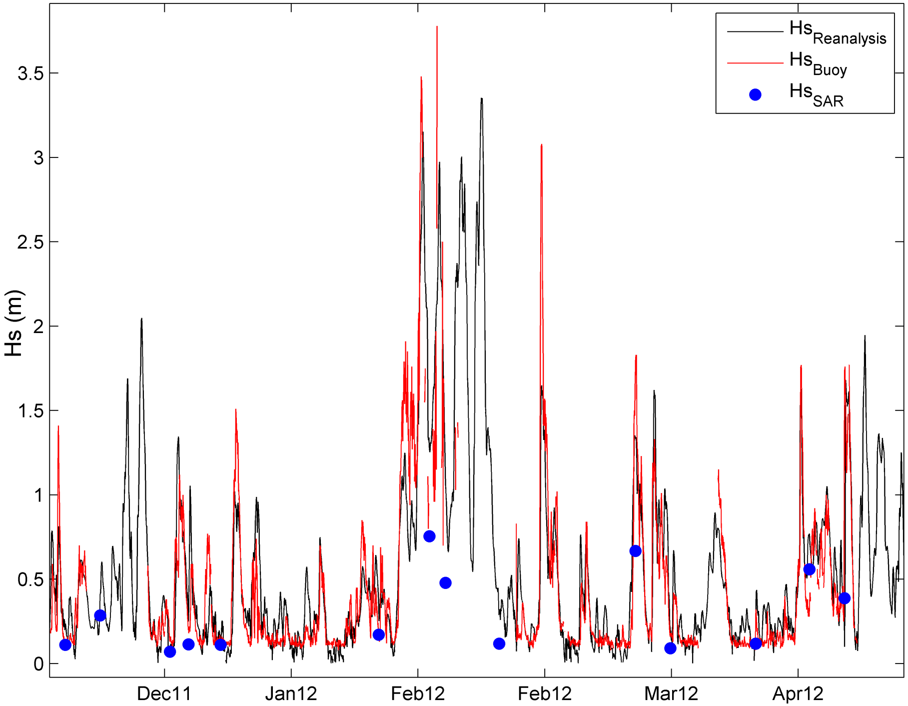

Figure 8. Comparison between the downscaled wave height series and the buoy wave height.

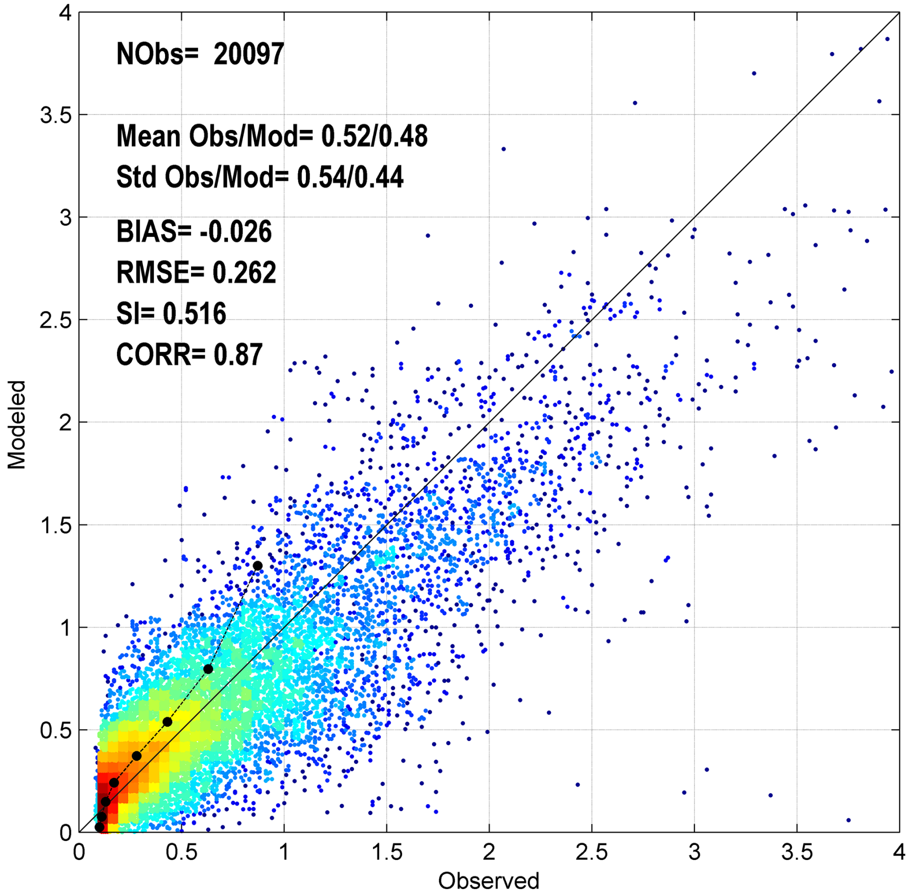

Figure 9. Quantile-quantile plot of observed and downscaled wave height.

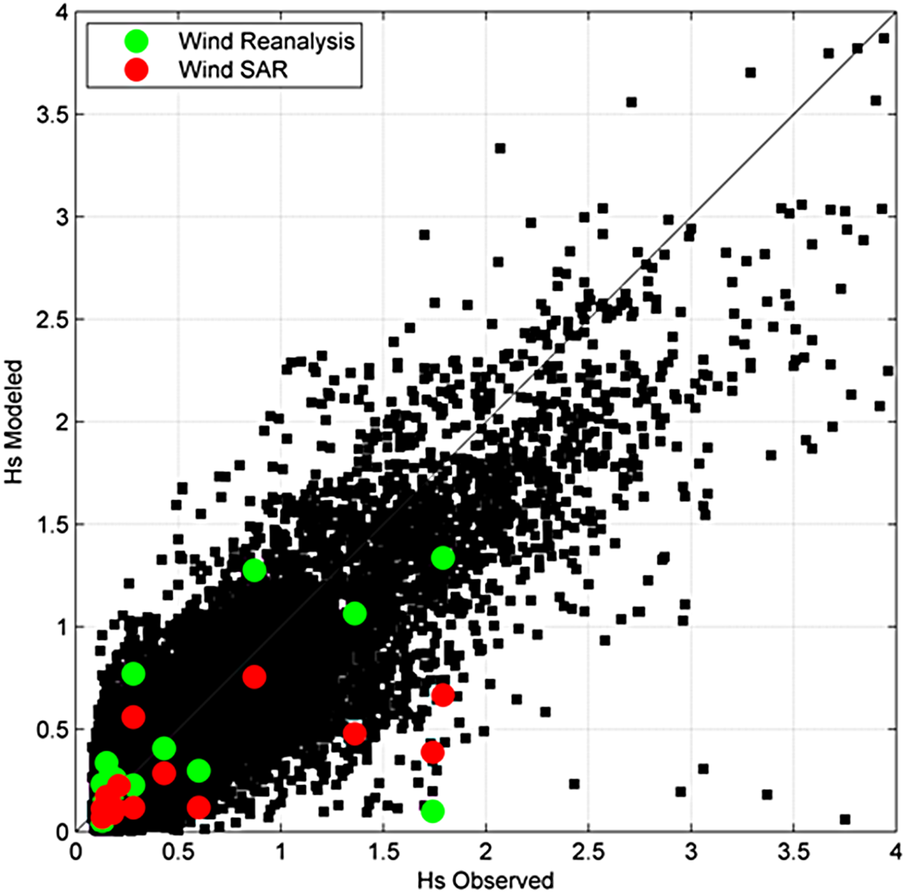

Figure 10. Quantile-quantile plot of observed and downscaled wave height including the SAR wind cases (red marks) compared to their respective modeled wind cases (green marks).