ON THE FEASABILITY OF THE USE OF WIND SAR TO DOWNSCALE WAVES ON SHALLOW WATER

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ABSTRACT

In this article 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.

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 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 [9].

To solve this problem is required to increase the spatial resolution of the simulations by means of a methodology for Downscaled Ocean Waves (DOW) [8] Therefore, wind and offshore wave databases are required as forcing in order to obtain high temporal coverage in the area of interest. Meanwhile the reanalysis wave databases are enough to describe the wave climate on the limit of simulations, frequently there is not available a wind reanalysis at an adequate spatial resolution to describe the wind structure near the coast. To resolve the wind fields detail it is likely that sub kilometer models will be necessary and possibly will require improved physics [19]. Alternatively, ocean surface wind field can be measured at high resolution (up to 300 m) and high frequency from remote sensing SAR. In this work, a wave downscaling is done on northern Adriatic Sea. Therefore several comparisons with the wave field forced with wind SAR datasets were done.

The SAR data provides an excellent spatial resolution and at the same time a high covering both spatial (large size of the observed scene) that time. In particular, the latter is made possible by the large number of available high-resolution SAR sensors and the ability to capture in all weather conditions and lighting. For these reasons, the SAR sensors are preferred to optical sensors for monitoring marine applications and are constantly used by government agencies, such as EMSA, and scientific (ECMWF) to monitor the state of the sea.

The study was aimed to demonstrate the ability of the use of remote sensing data to support the environmental management of mining offshore platforms. The variables studied are the fields of wind and waves.In addition to the analysis for major wind regimes in the study area, dates corresponding to intense long-lasting wind events have been investigated. The choice of the use of SAR data for the observation of these phenomena is justified by the conjunction of the following advantages of radar systems:

- short time to review and then possibility of monitoring variables that characterize the sea state;
- fast response of the acquisition system, which then allows the elaboration of data and synthetic estimates of the phenomena they are studying;
- high precision geo-location;
- ability to acquire during all light conditions (daytime/nighttime) and in all weather conditions.
- ability of polarimetry to enhance the estimation of the wind field and wave data that could be then used in the reanalysis.

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 Km 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 ENVISAT ASAR WS image acquired on 02/02/2012 21:00, 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 [2, 26, 14]. 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 [13]. 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 [12]. Bora is a downwelling favorable wind blowing from ENE with a mean speed of 15 m/s, shows an evident interannual variability [5] and can generate large waves with significant wave heights of 1 m, and period of 5 s [10]. In contrast, Sirocco is an upwelling favorable wind which blows from the southeast with a typical speed of 10 m/s and brings warm Mediterranean air [12] and generates lower wave height, but longer wave period in order of 10 s in the NAS region [25]. 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 [10, 19].

Reference [5] 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 [19, 1].

3. DATA

3.1. Wind

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) [9]. The resolution of modeled wind fields in the reanalysis is defined with 40 vertical hybrid levels (7 first levels below the first 1,000 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 (1992-2005) were used for the validations.

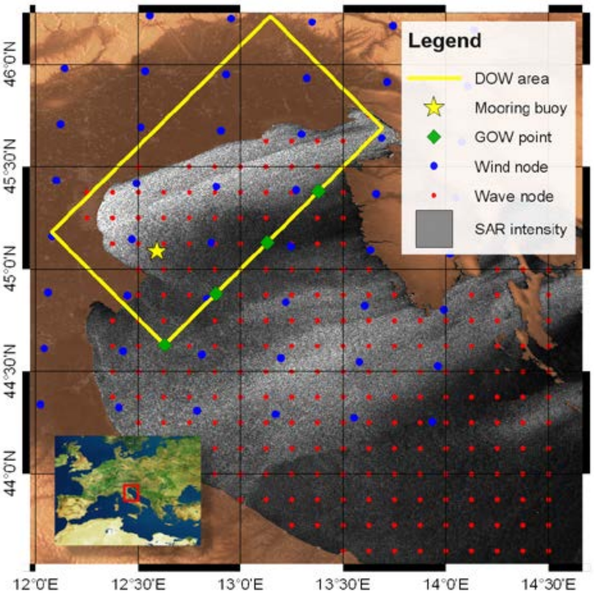

Figure 1. Northern Adriatic Sea. The yellow rectangle indicate the study area and the yellow mark a mooring buoy position. Red dots indicate the distribution of the GOW Mediterranean points and green dots the selected GOW points for downscaling. The blue dots indicate the SeaWind I nodes.

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 [6] for NRCS developed by for VV-polarized C-band scatterometry, using a priori wind direction from ECMWF 33 hours 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.

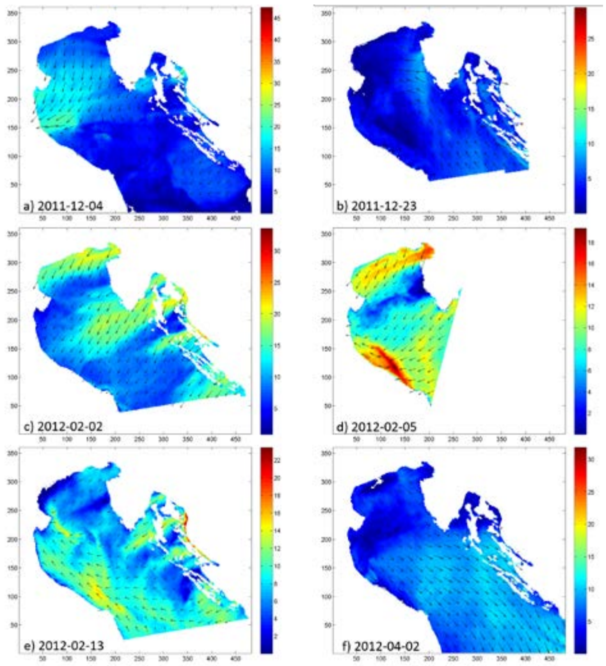

Figure 2. Some of the 15th SAR wind fields available for wave simulation.

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 [21], and [22]. 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 [23] and [24]. 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 (figure 3). Adequate configured model and input forcing have been used for each project. Detailed information about particular GOW projects can be found in [16] and [17].

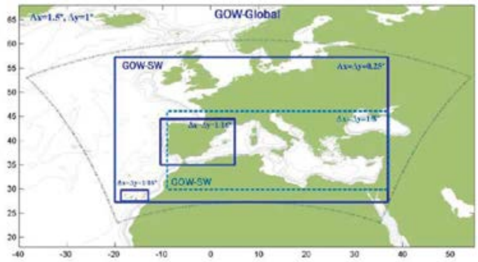

Figure 3. Wave reanalysis domains in Europe.

In particular, the GOW used in this work was forced with the CFSR reanalysis and spans from 1979 to present. The grid resolution in the Mediterranean is 0.18º (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 Figure 1), acquiring hourly the following parameters: Wave Height, Wave Direction, Wave Period.

4. METHODOLOGY

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 [8] in which a small number of waves and wind conditions were selected by means of the maximum dissimilitude method, propagated using the SWAN model [6], 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 figure 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 [8] 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 hour sea state.

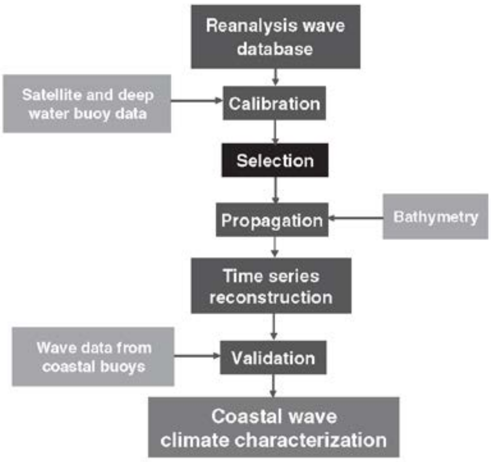

Figure 4. Methodology to downscale wave climate to coastal areas

5. WAVE DOWNSCALING

5.1. Setting

The methodology described on figure 4 was applied to northern Adriatic Sea. As inputs were used the GOW Mediterranean [9] grid with a spatial resolution of 0.18º (20 km) and the Seawind I database with a spatial resolution of 30 x 30 km (figure 5).

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 (figure 1) are 166 x 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 (Hs), the peak period (Tp), 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.

5.2. Calibration

Due to insufficient resolution of forcing wind fields and spatial and temporal model resolutions, a parametric calibration was done following [11]. 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.

$$H_s^C = a^R(\theta)\left[H_s^R\right]^{b^R(\theta)} \qquad (1)$$

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 [11].

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 degree.

5.3. Selection

The aim of the selection is to extract a subset of wave situations representative of available ocean conditions from the reanalysis database. The maximum-dissimilarity algorithm (MDA) has been proved to identify a subset of sea states comprising the most dissimilarity wave conditions in a database [7] even the extreme conditions, which is very suitable for the time series reconstructions using an interpolation technique. The algorithm is described in detail in [7].

This step of the methodology can be subdivided in several stages: 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 wave reanalysis nodes along the boundaries of the propagation domain and the simultaneous wind fields define the wave and wind forcing conditions of the wave simulations in shallow water, taking into account the wave spatial variability and the local wind wave generation. In this case, the GOW Mediterranean nodes, with spatial resolution of 0.18º, are used to define the boundaries of the DOW grid. The SeaWind I wind databases are used to define the wind fields, which are also the forcing used in the generation of the GOW reanalysis database. Figure 1 shows the dynamical downscaling grid, the GOW and Seawind nodes. The hourly sea state parameters in deep water, which are used in the selection process, and in the time series reconstruction process are: the significant wave height (Hs), the mean wave period (Tm) and the mean wave direction (θm) of every N nodes at the computation boundaries, and the time series of the wind directional components of the nodes at the upper boundary of the wind grid.

The hourly situations are highly correlated among different grid points of a given variable and among different variables. This high dimensionality is reduced applying the Principal Component Analysis (PCA), to extract as much correlations as possible from the spatial fields while maintaining the diversity of the climate situations. The PCA reduces the dimension of the data by means of a projection in al lower dimensional space preserving the maximum variance of the sample data. The eigenvectors of the data covariance matrix define the vectors of the new space. The idea of PCA is to find the minimum Empirical Orthogonal Functions (EOFs), so that the transformed components of the original data explain the maximum variance necessary for the problem at hand. Each PCA accounts for a fraction of the variability in the data in a decrease order. The criterion applied in this work for selecting an appropriate number of PCAs is based on the reconstruction root-mean-square-error (RMSE) of the offshore wave and wind conditions for an increasing number of PCAs (meaning the same that an increasing fraction of variance explained). In this work, a number d= 15 of PCs that explained 99.0% of the variance for the original data have been considered. Therefore, the dimension of the hourly wave and wind conditions is reduced from 35 to 15 with no significant information loss.

The next step consists of selecting a representative subset using MDA. For this purpose, the first element selected is the one with the largest significant wave height, identified in the original space. Figure 6 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.

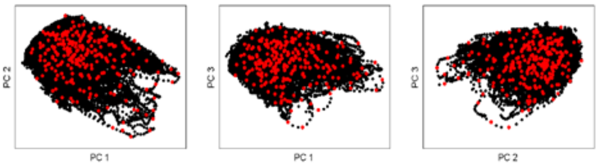

Figure 6. Subset of selected cases

5.4. Deep to shallow water transformation

The selected cases by MDA, representative of the wave climate in deep water, are propagated to coastal areas using the numerical model SWAN [6]. Different sea states parameters at the nodes of the DOW grids are stored for each case: the propagated significant wave height ($Hs_{p,j}$), the peak period ($Tp_{p,j}$) and the mean direction ($\theta m_{p,j}$). The subset of the M propagations in the downscaling domains defined a library (catalog) of cases formed by the M=100 hourly sea state parameters (Hs_p, Tp_p, $\theta m_p)_j$, corresponding to a certain sea state condition in deep water.

5.5. Time series reconstruction

The reconstruction of the time series of wave parameters in any of the nodes of the DOW grids is carried out by an interpolation technique based on radial basis functions (RBF), a scheme which is very convenient for scattered and multivariate data. A detailed description can be found on [9].

6. 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.

6.1. 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.

6.2. 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 reanalysis. Figure 7 show some examples of the comparisons between the wave fields forced with SAR winds and reanalysis winds.

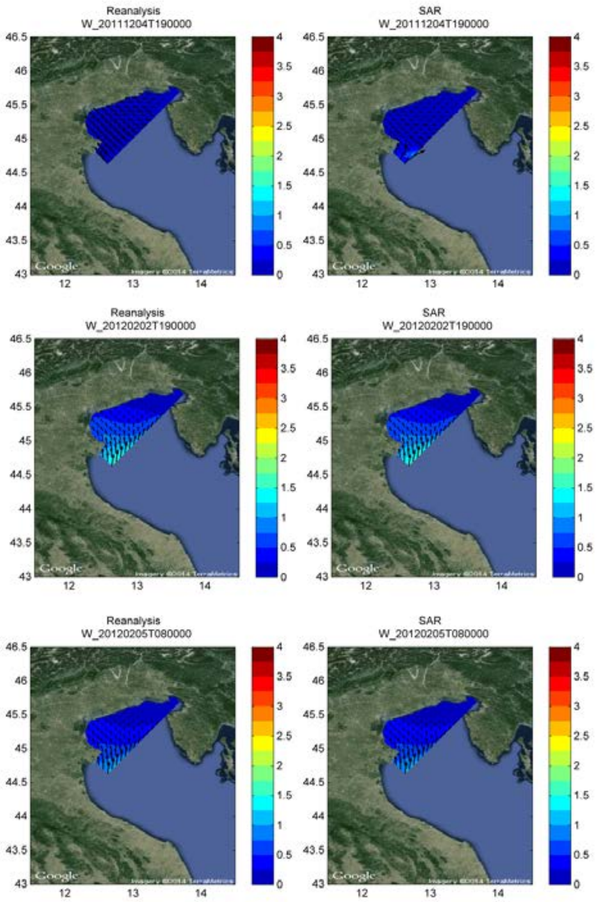

Figure 7. Some cases of waves fields forced with Reanalysis winds (left) and SAR winds (right).

7. RESULTS

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 (figure 8). 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.

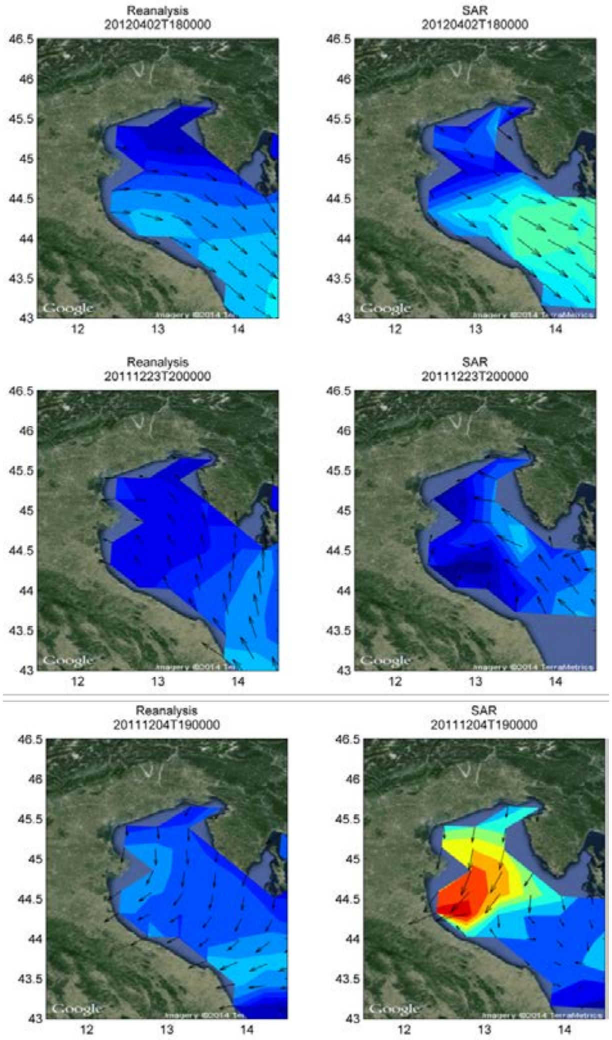

Figure 8. Examples of wind fields with similar patterns between SAR and Reanalysis.

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, 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.

To solve temporal resolution issue, the use of blended wind product from either SAR wind or modelled wind may represents a solution to supply SWAN model with consistent wind forcing, as successfully demonstrated in [4].

Figure 9 shows two segments of the reconstructed series for the buoy location and during the analyzed period. On the figure, the reanalysis and buoy heights are shown and the blue dots indicate the simulated wave height obtained using the SAR wind field as forcing.

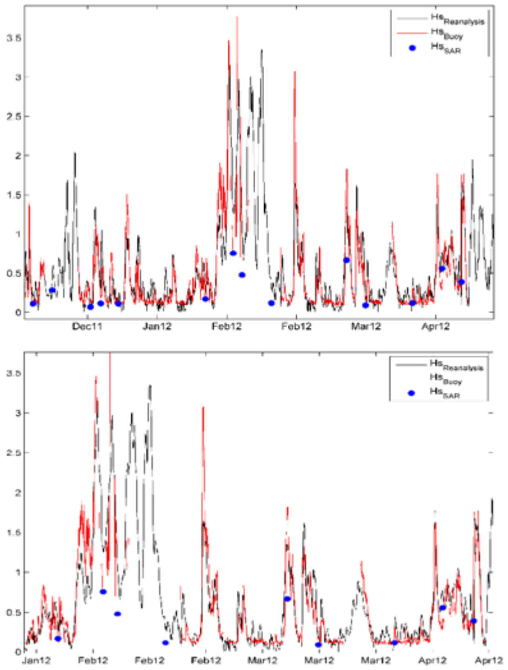

Figure 9. Comparison between the downscaled wave height series and the buoy wave height.

Figure 10 shows scatter and quantile-quantile (20 equally distributed Gumbel quantiles) plots of the measured versus modeled Hs, Tp for the entire dataset of each 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).

8. CONCLUSIONS

A wave climate downscaling of northern Adriatic Sea was done applying the methodology described on [8]. 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.

This research demonstrates how EO products, as SAR wind fields, can be successfully up-taken into oceanographic modeling. Operational SENTINEL-1 will produce a consistent long-term data archive (Level-2 – Ocean) built for these applications based on long time series.

Several SAR wind fields were analyzed and used to force the model to propagate the wind waves on the downscaled area. Results were compared to simulations forced with the SeaWind I wind fields. Although there are important differences between SAR and modeled wind fields, the downscaled wave field were very similar.

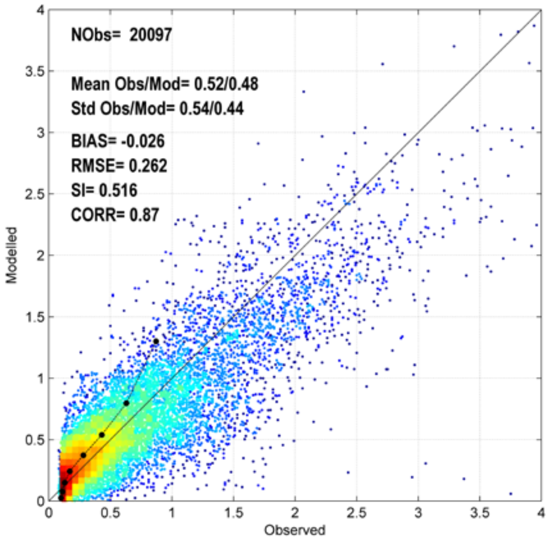

Figure 10. Quantile-quantile plot of observed and downscaled wave height.

9. ACKNOWLEDGEMENTS

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