SEA WAVE NUMERICAL SIMULATION AND VERIFICATION IN TYRRHENIAN COSTAL AREA WITH X-BAND COSMO-SKYMED SAR DATA

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ABSTRACT

In this paper, X-band COSMO-SkyMed© Synthetic Aperture Radar (SAR) data have been first used to force wind-wave interaction modeling in a coastal environment. The oceanographic model is based on the Third-Generation Simulating Waves Nearshore (SWAN) model, which is used for sea wave state estimation in coastal and island regions. The model is typycally forced through the Advanced Research Weather Research and Forecast (WRF-ARW) model data, which give the wind forcing at 1 hour intervals. In this paper, the SWAN model has been forced by using COSMO-SkyMed© SAR-based wind speed estimations, obtained by the azimuth cut-off procedure. After comparison with the ground truth, SAR-derived wind speeds have been used together with ECMWF wind directions to construct a blended wind product, which has been used to force the SWAN model. The validation has been accomplished with respect to significant winter wave storms occurred in the coastal area of Southern Tyrrhenian Sea.

Key words: COSMO-SkyMed; Sea Wave Simulation; Tyrrhenian Sea.

1. INTRODUCTION

Earth system dynamics and climate observation represents an active field of research in the context of the several key processes involved in the physical interaction between ocean surface and atmosphere boundary layer [1]. The monitoring of the different ocean and atmospheric variables involved in these processes is of major importance to better understand, characterise and predict their behaviour and their influence on climate. Within such a context, the interaction of wind, waves and currents is of great relevance for better understanding the behaviour of a coupled atmosphere-ocean circulation system where the ocean waves are the agent that transfers energy and momentum across the air-sea interface in accordance with the energy balance equation [1]. In fact, ocean waves play an important role in the interactions of the atmosphere and ocean. On the one hand, ocean waves receive energy and momentum from the atmosphere through wind input; on the other hand, through the process of white capping, ocean waves transfer energy and momentum to the ocean, thereby feeding the turbulent and large-scale motions of the oceans [1, 2]. Based on this rationale, the evolution of winds, waves and the wind-driven sea circulation should be studied for modeling and forecasting both weather and climate and are operationally interesting for the observation of both oceanographic phenomena, such as floods, storms and tides activities, and coastal management and risk assessment processes.

In literature, the wind-wave interaction modeling is well described by means of the Simulating Waves Nearshore (SWAN) model, the Third-Generation wave model, which computes random, short-crested wind-generated waves in coastal regions and inland waters [5, 6]. It was developed at National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction (NOAA/NCEP), and it gives the solution of the spectral action balance equations on the basis of a first and third order numerical scheme [6]. The model is operational since January 2005 at Dipartimento di Scienze Applicate (DSA) of the University of Naples Parthenope and it has been developed and adopted for simulating both waves generation and propagation in the Gulf of Naples. The model is typically forced by using wind field data provided through the Advanced Research Weather Research and Forecast (WRF-ARW) model data, the next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs [5, 6]. Outputs from the coupling of SWAN and WRF-ARW models include significant wave height (*Hs*) on gridded fields, with the associated wave directions (*Dw*) and periods (*Tp*), and the spectral information about wave energy at different wavelengths.

Recent advances in Earth observation (EO) technology have made possible improved global observations of several key parameters governing the ocean-atmosphere interactions. In the recent years, an increasing number of EO missions have provided an unprecedented capacity to observe the sea-surface and the atmosphere. Within such a framework, the use of X-band COSMO-SkyMed©

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Synthetic Aperture Radar (SAR) data is highly innovative. In fact, COSMO-SkyMed is a constellation of 4 satellites equipped with X-band microwave, high-resolution SARs able to operate in different modes, that ensure both a wide area coverage and a small revisit time, providing day- and night-time remotely sensing data [3]. Among the different acquisition modes available for each SAR sensor, i.e. Spotlight, StripMap (HImage and Ping Pong) and ScanSAR (Wide Region and Huge Region) modes, the ScanSAR Huge Region one is very interesting from an operational viewpoint, since it performs a grouping of acquisitions over adjacent sub-swaths, which allow achieving large ground coverage of about $200km$ in both range and azimuth direction with a spatial resolution of $100 \times 100m$, respectively [3]. However, X-band peculiarities make the modelling of coastal oceanographic processes a non trivial task, due to the presence of atmospheric phenomena, which affect both SAR images and the estimation of key geophysical parameters governing oceanographic phenomena [4].
In this paper, X-band COSMO-SkyMed© SAR data have been first used to force the SWAN model in a coastal environment. The proposed model has been first forced by using COSMO-SkyMed© SAR-based wind speed estimations, which have been retrieved by means of the azimuth cut-off procedure [7, 8]. The key step of this SAR wind speed retrieval is the estimation of the azimuth cut-off wavelength from its autocorrelation function and its transformation into wind speed by means of a semi-empirical model [7, 8]. The major advantage of this procedure is that it does not require any *a priori* information of wind direction. SAR data set used for the study consists of 60 X-band Level 1B Multi-Look Ground Detected (DGM) ScanSAR Huge Region mode VV-polarized COSMO-SkyMed© SAR data, gathered in the Southern Tyrrhenian coastal area during the Summer and Winter Seasons of 2010. SAR-derived wind speeds have been analyzed and compared to the ground truth provided by ECMWF model data in order to demonstrate the consistency of wind speed retrievals. Hence, COSMO-SkyMed© SAR-derived wind speeds have been used together with ECMWF wind directions to construct a blended wind product, which has been used to force the SWAN model. The validation has been accomplished with respect to some significant wave storms occurred in the coastal area of Southern Tyrrhenian Sea during the winter season of 2010. Within such a framework, the ground truth has been provided by both timely and spatially co-located national and regional buoys wave field data and ASCAT scatterometer winds. The improvement obtained by using this blended wind field product instead of the classical wind-wave buoys data has been finally discussed.
The paper is organized as follows: the methodology at the basis of wind-wave interaction modeling and the SAR-based wind estimation technique are outlined in Section2, experimental results are described in Section 3 and conclusions are drawn in Section 4.

2. METHODOLOGY

In this section the wind-wave interaction modeling used for the purposes of the paper is briefly outlined together with the COSMO-SkyMed SAR-based wind speed estimation technique.

2.1. Wind-Wave interaction modeling

The wind-wave interaction modeling is a multiple-connected modelling system, specifically conceived for wave forecast, which is based on the SWAN model [5, 6]. It describes the temporal and spatial variation of the wind-induced surface elevation, the whitecapping effects and the friction with the sea bottom layer [5, 6]. The propagation of the wave action density spectrum ($N = F/\sigma$) is given by [6]:

$$\frac{DN}{Dt} = \frac{S}{\sigma} \quad , \tag{1}$$

where D/Dt represents the total derivative, S is the effect of the difference between the inner and the outer energy for the spectrum F and σ is the intrinsic frequency. The generation terms used in the SWAN model for the evaluation of S are:

- Input term of wind-wave Energy, S_{in}.
- Whitecapping term, S_{ds}.
- Non-linear term of wave-wave interaction, S_{nl}.
- Term of interaction with the sea bottom layer, S_{bot}.

The model has been typically coupled with WRF-ARW model data [5, 6], which give the wind forcing at $1-h$ intervals. It has been implemented using a four-nested grid configuration covering the Mediterranean Sea up to the Gulf of Naples, where the inner mesh has the higher resolution ($1 \times 1km$). Outputs from the coupling of SWAN and WRF-ARW models include significant wind-wave intercation parameters, such as *Hs*, *Dw* and *Tp*.

2.2. COSMO-SkyMed SAR Wind Speed Estimation Technique

SAR wind speed estimation technique based on the azimuth cut-off procedure is described and detailed for X-band COSMO-SkyMed© SAR data.
SAR-based wind field estimation is strongly affected by SAR data quality, hence a pre-processing analysis has been accomplished, aimed at improving the image quality of X-band Level 1B DGM ScanSAR Huge Region mode VV-polarized COSMO SkyMed© SAR measurements.
COSMO-SkyMed© SAR data may be severely affected by two problems: the scalloping and atmospheric/tropospheric phenomena. The first one, which is

a peculiarity of ScanSAR acquisition mode, consists of periodic processing anomalies along the azimuth direction, which affect the accuracy of SAR-based wind speed estimation [9]. The second one is a peculiarity of X-band SAR data, which can be dominated by tropospheric and atmospheric phenomena thus affecting SAR imagery interpretability [4, 9].

To effectively account for both the above-mentioned phenomena, an automatic two-steps processing chain, first developed in [9], has been here adopted to improve the quality of SAR images. The first step aims at removing the scalloping pattern in X-band ScanSAR COSMO-SkyMed© SAR data by means of a filtering technique based on the Discrete Wavelet Transform (DWT) [10]. The second step consists of a test of homogeneity based on the variance to mean square ratio (VMSR) of SAR image power spectral density, which allows identifying parts of SAR data affected by atmospheric phenomena [11].

Following the pre-processing analysis, SAR wind speed estimation has been undertaken by extending the azimuth cut-off procedure first proposed for C-band SAR data in [7]. The key step of this procedure is the estimation of the azimuth cut-off wavelength (λ_c) from SAR image autocorrelation function (ACF) and its transformation into wind speed by means of a semi-empirical model [7]:

$$U_{10} = 4.75(\frac{\lambda_c - \Lambda}{110}) \quad , \tag{2}$$

where U_{10} is the wind speed at 10m above the sea surface, λ_c is the azimuth cut-off wavelength and Λ is the nominal azimuth resolution. It must be explicitally pointed out that this technique does not require any *a priori* information on wind direction [7, 8]. A grid size of 12.5×12.5 km has been used for wind speed estimation in order to carefully and robustly compare the SAR derived wind speed retrievals with a valuable ground truth provided by both ECMWF model and ASCAT scatterometer wind data.

3. EXPERIMENTAL RESULTS

In this section some meaningful experiments related to the application of the SWAN model in a coastal environment are presented and discussed.

The test area is the coastal zone of the Southern Tyrrhenian Sea, including the gulfs of Gaeta, Napoli, Salerno and Policastro, which are of great applicative relevance for both oceanographic and coastal-maritime surveillance purposes.

The data set consists of:

- 60 X-band Level 1B DGM ScanSAR Huge Region mode VV-polarized COSMO-SkyMed© SAR data, collected in the test area during the Summer and Winter Seasons of 2010. They provide a ground coverage of about $200km$ in both range and azimuth direction with a spatial resolution of $100 \times 100m$, respectively.

- Timely and spatially co-located ECMWF model data, with a spatial and time resolution of $0.2°$ and $6h$, respectively.

- Timely and spatially co-located ASCAT scatterometer data, with a spatial resolution of $12.5 \times 12.5km$.

- Timely and spatially co-located wave field data provided by *in situ* national and regional buoys system observations. In particular, national wave data have been retrieved by Rete Ondametrica Nazionale (RON), on the locations of Ponza (on the Northern bound of the Gulf of Gaeta) and Cetraro (on the Southern bound of the Gulf of Policastro), while the regional wave data have been retrieved by the Campania buoy network on the locations of Capri (offshore the Gulf of Naples) and offshore Acciaroli (in the Gulf of Salerno).

Experiments can be summarized into three steps.

The first one aims at evaluating the estimation accuracy of the proposed wind-wave interaction modeling with respect to *in situ* wave buoys observations. Accordingly, preliminary simulations of the SWAN model have been accomplished with forcing provided by ECMWF model data. Outputs from these simulations, which include *Hs*, *Dw* and *Tp*, have been properly compared with the buoys-related ones.

The seond step aims at evaluating the consistency of COSMO-SkyMed© SAR-derived wind speed estimations with respect to the ground truth provided by ECMWF model data, *in situ* wave buoys observations and ASCAT scatterometer wind fields. Within such a framework, SAR wind speed estimation has been accomplished through the azimuth cut-off procedure.

The third step aims at evaluating the estimation accuracy of the SWAN model with forcing provided by COSMO-SkyMed© SAR-derived wind speed estimations. Within such a framework, experimental simulations of SWAN model have been accomplished with forcing provided by blended wind field products, i.e. COSMO-SkyMed© SAR-derived wind speeds and either *in situ* or ECMWF wind directions. Simulated parameters, i.e.*Hs*, *Dw* and *Tp*, have been properly compared with both buoys- and WRF-related ones.

For each step, the validation has been accomplished with respect to significant wave storms and tidal events occurred in the Southern Tyrrhenian Sea during the summer and winter seasons of 2010.

3.1. Preliminary Simulations of SWAN Model

In this sub-section, preliminary simulations of SWAN model are described, with forcing provided by ECMWF wind model data. Some meaningful results are shown, which are relevant to the significant winter wave storm of December $17 - 18^{th}$ 2010.

The comparison between the simulated and recorded waves at the location of Ponza is shown in Fig.1. It

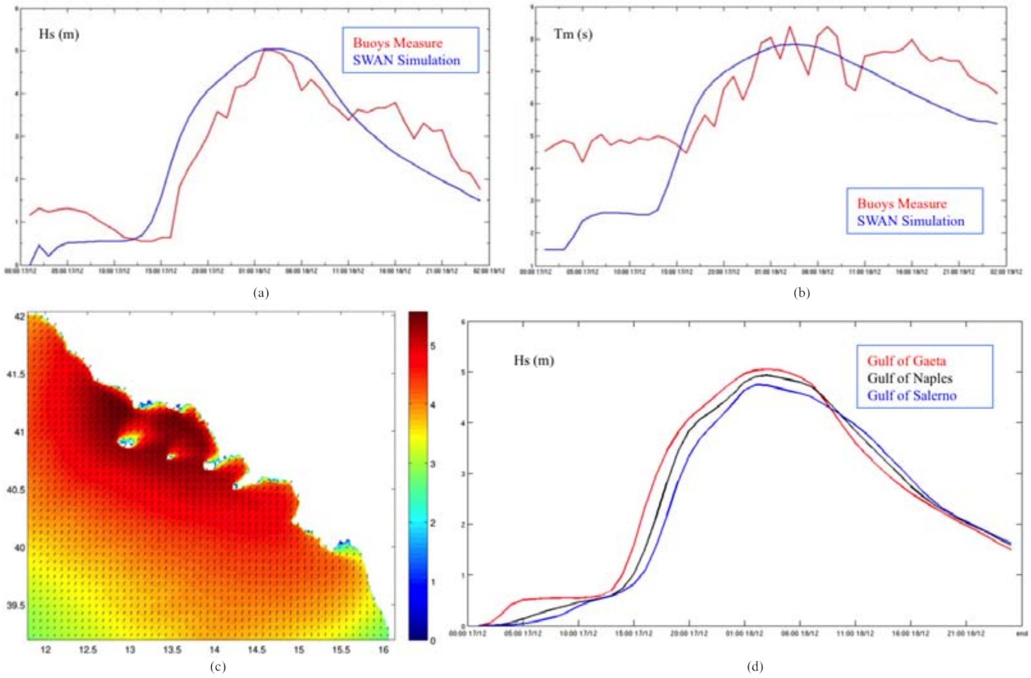

Figure 1. Comparison between buoys observations (red line) and SWAN simulations for the winter storm of December $17-18^{th}$ 2010*. (a)* $Hs(m)$*. (b)* $Tm(s)$*. (c) Significant wave height and direction, simulated on the whole coasta area of Southern Tyrrhenian Sea. (d) Significant wave height simulated on the location of Gulfs of Gaeta (red line), Naples (black line) and Salerno (blue line).*

can be noted that a negligible error is present in *Hs* estimation, with a perfect agreement at the storm apex. In fact the comparison between simulated and buoys-related Hs gives the same value of $5.0m$ at the peak of the storm in the same hour. Non-negligible errors are present in Tp and Dw estimations, especially at the initial and final stage of the storm, in which the simulations have been more critical. Other results are summarized in Fig.**??**, where the SWAN model have successfully provided meaningful simulation results in terms of both Hs and Dw, for the locations of Gaeta, Naples and Salerno (see Fig.**??**). The agreement between numerical simulation results and buoys observations demonstrates the effectiveness of the SWAN model for the modeling of ocean-atmosphere interaction processes. Experimental results show that ECMWF wind model data represent a suitable forcing of the SWAN model for the estimation of significant wind-wave interactions parameters.

3.2. COSMO-SkyMed SAR Wind Field Estimation

In this sub-section some meaningful experimental results are described, which are relevant to the COSMO-SkyMed© SAR wind speed estimation based on the azimuth cut-off procedure. First experiment is relevant to the COSMO-SkyMed© SAR acquisition of June 19^{th} 2010, where a significant wave storm occurred ($Hs \leq 2.0m$). The VV-polarized normalized radar cross section (NRCS) image of X-band Level 1B DGM ScanSAR Huge Region mode COSMO-SkyMed© SAR data is shown in graytones in Fig.2(a), where both the scalloping effect and weak atmospheric phenomena are in place. It must be noted that SAR image quality has been successfully improved by sorting out both scalloping and atmospheric phenomena (not shown to save space). COSMO-SkyMed© SAR-derived wind speed estimation based on the azimuth cut-off procedure is shown Fig.2(c), where the ground truth calls for wind speed ranging between $5-12m/s$ (see Fig.2(d)). To consistently compare wind products with the provided ground truth, ECMWF model data have been interpolated bilinearly inside the SAR image domain over a grid size of $12.5 \times 12.5km$, according to the processing chain of the azimuth cut-off procedure. With this respect, a rough comparison between SAR-derived wind speeds and the provided ground truth is shown in Fig.2(e), where non-negligible differences are present along the coastal area of the SAR image domain. However, experimental results are very significant and do not limit the consistency of COSMO-SkyMed© SAR-based wind speed estimation. In fact, ECMWF model data both suffer from uncertainty over the sea, especially along the coastal area, and they are not able to capture small scale features, which can be revealed by means of SAR data. Experimental results shown in Fig.2 demonstrate that it is possible to get a consistent wind speed estimation even at X-band by means of the azimuth cut-off procedure. Furthermore, experimental results show the full benefits of X-band Level 1B DGM ScanSAR Huge Region mode COSMO-SkyMed© SAR data for wind speed estimation purposes.

Second experiment is relevant to the COSMO-SkyMed©

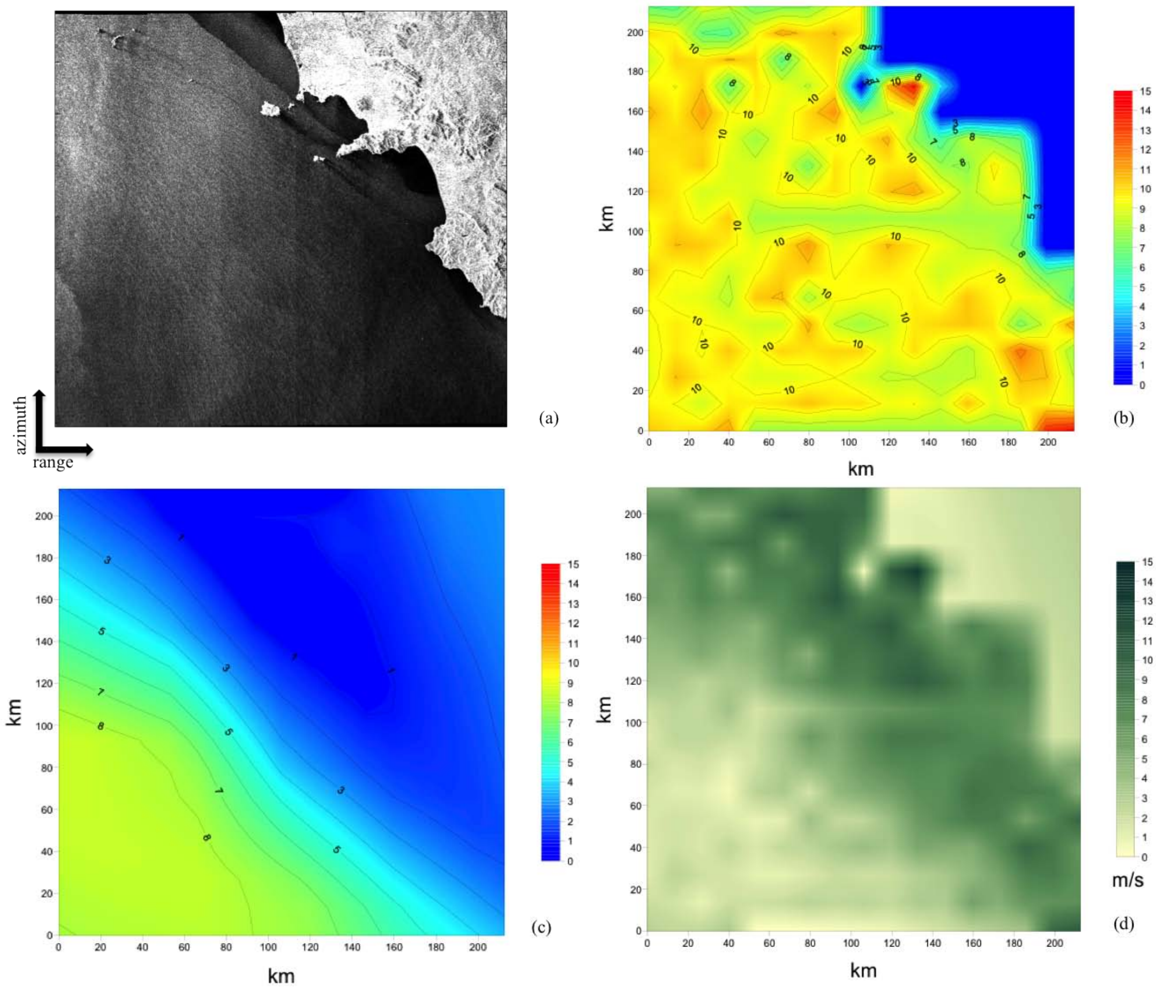

Figure 2. X-band Level 1B DGM ScanSAR Huge Region mode COSMO-SkyMed© SAR data acquired on June 19^{th} 2010 *in the coastal area of Southern Tyrrhenian Sea. (a) VV-polarized normalized radar cross section (NRCS) image. (b) Land Masked pre-processed VV-polarized NRCS image. (c) Wind speed retrieval. (d) Ground truth. (e) Comparison between ECMWF and COSMO-SkyMed© SAR-derived wind speeds. COSMO-SkyMed product©-ASI-Agenzia Spaziale Italiana-*2010*. All rights reserved.*

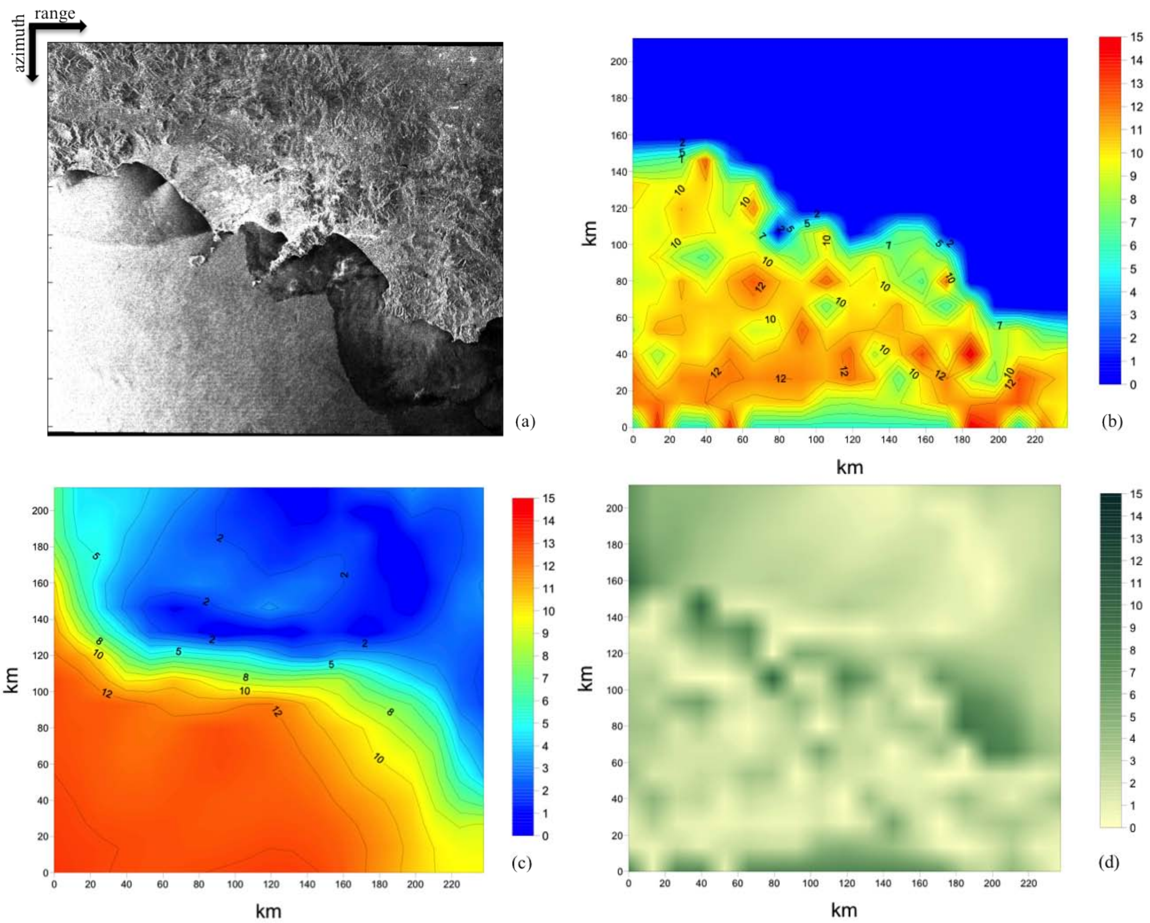

Figure 3. X-band Level 1B DGM ScanSAR Huge Region mode COSMO-SkyMed© SAR data acquired on December 17^{th} 2010 *in the coastal area of Southern Tyrrhenian Sea. (a) VV-polarized NRCS image. (b) Wind speed retrieval. (c) Ground truth. (d) Comparison between ECMWF and COSMO-SkyMed© SAR-derived wind speeds. COSMO-SkyMed product©-ASI-Agenzia Spaziale Italiana-*2010*. All rights reserved.*

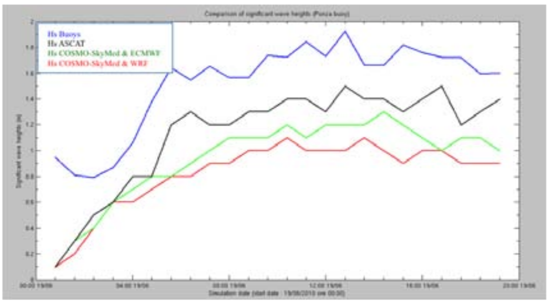

Figure 4. Simulated and recorded Hs for the summer storm of June 19^{th}2010. Comparison among buoys (blue line), ASCAT (black line), blended COSMO-SkyMed SAR and ECMWF (green line), and COSMO-SkyMed SAR-derived wind fields (red line).

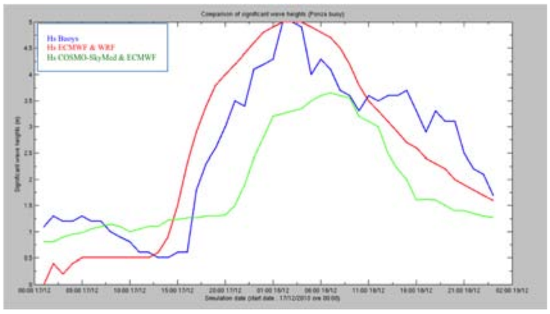

Figure 5. Simulated and recorded Hs for the summer storm of December $17-18^{th}$2010. Comparison among buoys (blue line), ECMWF (red line) and blended products of COSMO-SkyMed SAR-derived and ECMWF wind fields (green line).

SAR acquisition of December 17^{th} 2010, where a significant wave storm occurred ($Hs \leq 2.0m$). The VV-polarized NRCS image of X-band Level 1B DGM ScanSAR Huge Region mode COSMO-SkyMed© SAR data is shown in graytones in Fig.3(a), where only the scalloping effect can recognized in SAR imagery. The output of COSMO-SkyMed© SAR-based wind speed estimation technique and the relevant ground truth provided by ECMWF model data are shown in Fig.3(b)-(c), respectively. The rough comparison between SAR-derived wind speeds and the provided ground truth is shown in Fig.3(e), where again non-negligible differences have been experienced along the coastal area of SAR image domain. Experimental results agree with the previous one, thus demonstrating the effectiveness of the azimuth cut-off procedure and X-band Level 1B DGM ScanSAR Huge Region mode COSMO-SkyMed© SAR data for wind speed estimation purposes.

3.3. ECMWF and COSMO-SkyMed SAR wind field products to force the SWAN model

In this sub-section, some meaningful experimental results are presented and discussed to validate the estimation accuracy of the proposed SWAN model with forcing provided blended products consisting of COSMO-SkyMed© SAR-derived wind speed and ECMWF wind direction.

A first meaningful set of results is shown in Fig.4 for the summer storm of June 19^{th} 2010 ($Hs \leq 2.0$ m), where *in situ* buoys observations are compared with numerical simulations of the SWAN model accomplished by means of (a) ASCAT scatterometer winds, (b) blended COSMO-SkyMed© SAR-derived wind speed and ECMWF wind direction, and (c) blended COSMO-SkyMed© SAR-derived wind speed and WRF wind direction, respectively. Experimental results are quite satisfactory, since COSMO-SkyMed© SAR-derived wind speed retrievals allow catching the changing storm characteristics, although the peaks of the storm is quite underestimated. Compared to both buoys observations and ASCAT scatterometer winds, best results are obtained with the blended wind field products consisting of COSMO-SkyMed© SAR-derived wind speed and ECMWF wind direction. Numerical simulations demonstrate that the SWAN model is able to provide significant and accurate sea wave estimations even by using blended wind field product composed by both model and remotely sensed estimations. In detail, the blended use of COSMO-SkyMed© SAR wind speed and ECMWF wind direction represents a consistent wind forcing for both the SWAN model and the estimation of wind-wave interaction parameters.

A second meaningful set of results relevant to the winter storm of December $17-18^{th}$ 2010 ($Hs \leq 5.0m$) are shown in Fig.5, where *in situ* buoys observations are compared with numerical simulations of the SWAN model accomplished by means of (a) blended ECMWF and WRF wind fields and (b) blended COSMO-SkyMed© SAR-derived wind speed and ECMWF wind direction, respectively. Numerical simulations agree with previous results. In summary, very good and accurate results are obtained by forcing the SWAN model with COSMO-SkyMed© SAR-derived wind speed estimations, which are able to both catch the storm trend and estimate *Hs* values with an underestimation of $20-30\%$ at the storm peak. This is an important result, which can be used for further research relevant to the use of X-band COSMO-SkyMed© SAR data as alternative integrated source of wind information. Furthermore, experimental results have shown that, at the present state, a blended wind product including both ECMWF model data and COSMO-SkyMed© SAR-derived wind speeds can provide valuable improvements of wind-wave interaction modeling.

4. CONCLUSIONS

In this paper X-band ScanSAR Huge Region mode COSMO-SkyMed© SAR data have been first used to force wind-wave interaction model in a coastal environment. The oceanographic model is based on the SWAN wave model, which is typically forced by WRF wind model data. In this study, the SWAN model has been first forced by using COSMO-SkyMed SAR-based wind speed, which has been retrieved by means of the azimuth cut-off procedure. The test area is the coastal zone of Southern Tyrrhenian sea, where some significant wave storms are accounted for the purposes of the paper. Experimental results demonstrate that:

- The SWAN model is able to provide significant and accurate sea wave state estimations with forcing provided by ECMWF model data. In fact, a significant agreement between numerical simulation results and *in situ* buoys observations is here experienced for wind-wave interaction parameters.
- The azimuth cut-off procedure is able to both provide consistent wind speed estimations even at X-band and take full benefits of X-band ScanSAR Huge Region mode COSMO-SkyMed© SAR data as alternative source of wind speed.
- The use of blended wind field products, i.e. COSMO-SkyMed© SAR-derived wind speeds and either *in situ* or ECMWF wind directions, successfully represents a consistent wind forcing for both the SWAN model and the estimation of wind-wave interactiuon parameters.
- The SWAN model can be really improved by using COSMO-SkyMed© SAR data as alternative integrated source of wind information.

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