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An integrated approach of in-situ data, remote sensing measurements and numerical simulations to study storm events in the Ligurian Sea

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***Abstract* – Extreme weather events have significant impacts on human activities and related economy in coastal areas. In this scenario, the forecast of sea storms and sea level changes to mitigate the effects of waves on shores, piers and critical coastal infrastructures is a key but challenging goal. This objective can be effectively achieved using a synergistic approach that includes numerical models, in-situ data and remote sensing measurements.**
To this end, we investigated the atmospheric forcing data of the storm event occurred in the Ligurian Sea on 29-31 October 2018, which induced significant damages with coastal defenses collapses, loss of property and infrastructure. The study was carried on using a dataset that consists of atmospheric and sea wave data from RNM stations, sea wind field data from satellite radar and WRF model numerical simulations.
The experimental results demonstrate the effectiveness of the proposed integrated approach, showing that ASCAT wind speeds agree well with the numerical simulations with deviations in most locations limited to 3 m/s, except in presence of complex orographic features.

I. INTRODUCTION

Understanding our oceans is critical to protect people from natural disasters and the impending challenges of changing climate. Our ability to forecast weather and global climate changes, thus minimizing the disastrous effects of cyclones, storm surges and tsunamis, strongly depends on our capability to observe the changes in atmosphere and ocean in real-time at spatial and temporal scales with the required resolution and accuracy. In order to analyse the reliability of the remote sensing data and in-situ measurements for the validation of wind, sea level and atmospheric pressure numerical simulations, we selected the "Vaia" storm event occurred over the Ligurian Sea on 29-31 October 2018, that produced many damages along the coast of Liguria region. In particular, in the Savona coastal area the storm resulted in the almost complete destruction of the structures and piers of the bathing facilities and the removal of entire stretches of sandy and pebble beaches. Santa Margherita Ligure and Rapallo harbours were particularly affected, with the collapse of the respective breakwaters and damage of many leisure boats, as shown in Fig 1. Towards Portofino, the storm event caused the entire collapse of a section of provincial road near Paraggi.

Fig. 1. Leisure boats damaged in the Rapallo harbour due to the considered storm event. Source: Il secolo XIX, digital photograph (accessed 17 September 2020).

Nowadays there are several remote sensing tools that allows providing information on the sea state including significant wave height, currents and surface wind field. In particular, microwave satellite sensors as radar altimeters, scatterometers and SARs represent a valuable ocean data source that routinely offers day-and-night observations at different temporal and spatial scales even under adverse weather conditions, e. g., cloud cover, rain cells and storms.
When dealing with wind field retrieval, satellite SAR sensors can provide high-resolution imagery of the sea surface on a local scale with weekly imaging capabilities [1]. Hence, if larger-scale ocean events must be monitored where denser revisit time is needed while fine spatial resolution is less demanding, spaceborne real aperture radars, i. e., scatterometers, are the most operationally-significant tool even during storm events [2, 3].
In this study, satellite radar data from ASCAT (Advanced Scatterometer) are exploited for sea wind speed retrieval to support in-situ measurements and numerical modeling. ASCAT is a C-band (5.255 GHz) scatterometer on-board

of the EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) Metop (Meteorological Operational Satellite) satellites. ASCAT measures the VV-polarized normalized radar cross section (NRCS) according to two sets of fan-beams, one on each side of the satellites, covering 550 km-wide swath each with an incidence angle that spans from 25° to 65°. As a result, an approximately twice global daily coverage at mid-latitudes is achieved due to both ascending and descending swaths and a daily coverage of 65% of the Earth achieving a global coverage after five days [4]. Multiple NRCS measurements ensuring incidence angle diversity are undertaken to retrieve the wind vector according to an ill-posed inverse problem.

In Di Luccio et al. [5] we compared numerical and experimental data to detect the atmospheric pressure drop and consequent sea level alteration in the Ligurian Sea during this storm event. We reconstructed the spatial and temporal evolution of the storm event making use of a high spatial resolution weather-sea off-line coupled forecasting system, and several in situ measurements, consisting of sea level (SL), wind and sea level pressure. Hence a strong need was felt to augment some of these simulations and surveys with spaceborne radar measurements in order to avoid the smoothed wind speed results due to the sheltered position of the weather stations. To do this, we propose an integrated approach to analyse this hazardous and destructive storm event. The analysis has been carried out with the aim of numerical simulations, as in [5],together with satellite remote sensing wind field measurements. The numerical simulations were carried out on the atmospheric domain, through the configuration of Weather Research and Forecasting (WRF) model [6], which already supported some studies on coastal dynamics [7, 8].

In the past, we compared numerical simulations of winds and waves with SAR-derived field observations [9, 10, 11, 12] both for coastal oceanographic studies and for Marine Spatial Planning purpose [13]. In the present study, we compare the results of the WRF numerical simulations with the wind speed (WS) remote sensing observations provided by satellite radar data from ASCAT (Advanced Scatterometer). ASCAT measurements allow obtaining the sea wind field at 10 m above sea level at neutral conditions with a 12.5 km spatial resolution. These scatterometer observations have similarities and differences to SAR ones: the spatial resolution is coarser than for a SAR instrument, while the revisit time is more regular, because a scatterometer can provide one or two observations per day over most globe, whereas SAR sensing is more irregular [14].

II. MATERIAL AND METHODS

In this section, the dataset considered for the study of the "Vaia" storm event is presented. It includes in-situ data and spaceborne radar measurements that were both compared with atmospheric and wave numerical models.

A. Atmospheric in-situ observations

We collected data, with a 1/6 h timestep, available from the RMN stations of Genova (44°24'36.46"N, 08°55'31.86"E) and Livorno (43°32'46.63"N, 10°17'57.62"E), hereafter called P1 and P2, respectively [5]. All the stations provide data on sea level (SL) with millimeter precision since 2010 with a radar coupled with the historical ultrasonic hydrometer sensor equipped since 1998. The stations are also equipped with an anemometer measuring wind speed (WS) and direction (WD) 10 meters above the sea level, a barometer recording the sea level pressure (SLP), an air and water temperature sensor, as well as a relative humidity sensor.

B. Remote sensing observations

Sea wind field maps from scatterometers as ASCAT can be obtained from an empirical relationship between the measured NRCS and the wind vector, i. e., wind speed V and relative direction with respect to the scatterometer antenna beam ϕ. This relationship is termed as a Geophysical Model Function (GMF) and, at C-band, the most common GMF family is the CMODs, whose general expression is given by [15]:

$$z = B_0(V,\theta)[1 + B_1(V,\theta)cos\phi + B_2(V,\theta)cos2\phi] \quad (1)$$

where θ is the radar incidence angle, $z = \sigma_0^0.625$, B_0 is the bias term, B_1 describes the up/downwind- modulation and B_2 describes the signal modulation induced by the main wind direction.

It is worth noting that the accuracy and the reliability of the sea wind field retrieval are significantly affected by rain and land NRCS contamination, with the former that can be neglected at C-band while the latter that can be effective close to the coast. Note also that, due to non-linear modulation processes, scatterometers tend to underestimate extreme wind speeds (> 25 m/s).

For the purpose of this study, in order to provide reliable and spatially-distributed offshore wind speeds, the global wind level-3 ASCAT products consisting of the sea wind field at 10 m above sea level at neutral conditions [16] derived over coastal areas at 12.5 km spatial resolution are considered over the selected study area. They were provided by the Jet Propulsion Laboratory (JPL) through the PODAAC (Physical Oceanography Data Access) web platform (podaac.jpl.nasa.gov/dataaccess). The CMOD7 geophysical model function (GMF) is used to generate the wind field map from the NRCS measurements that results in high accuracy, i. e., $\leq$ 2 m/s within 12-20 km from the coastline [17, 18].

C. *Numerical models*

A high spatial resolution weather forecasting system was configured using High Performance Computing (HPC) infrastructure to manage and run the open-source model components WRF. The atmospheric model WRF-ARW computes the 10 m wind fields and other atmospheric parameters. In order to produce the numerical simulations presented in this paper, we configured the WRF model, initialized with the Global Forecast System (GFS) produced by the National Center for Environmental Prediction (NCEP), with two-way nested computational domains: a coarser domain ($d01_{WRF}$) covering the whole Europe and a finer domain ($d02_{WRF}$) covering the Italian peninsula, with about 25 km and 5 km spatial resolution, respectively. The wind numerical models already supported some studies on coastal dynamics [7], coastal vulnerability assessment [8] and coastal management [9], also in combination with SAR-derived field observations [10, 11].

III. EXPERIMENTAL RESULTS

During the considered storm event, as reported in [5], the comparison between the simulated wind fields and in-situ wind observations at Livorno and Genova ISPRA weather stations show numerical wind speeds higher than 10 m/s coming from W and SW. In addition, numerical and observed pressure data both reported a significant pressure drop, down to 990 mb, see Fig. 2.

Corresponding wind speed maps were derived over the study area from the ASCAT scatterometer measurements, in order to provide reliable offshore information on the storm event.

According to Verhoef et al. [17] the scatterometer wind measurement and the simulated wind are considered to be co-located when the acquisition time difference in less than 30 minutes. Results are shown in Fig. 3, where the subfigure (a) refers to the simulated wind speed from the WRF numerical model and subfigure (b) refers to ASCAT wind vector obtained during the morning of 30 October, respectively. There is a fairly good agreement between the two wind maps, with the comparison suggesting that the satellite scatterometers represent a reliable source for offshore wind speed information, since they provide WS values consistent with the storm event, i. e., about 20 m/s.

A quantitative comparison is also performed whose results are listed in Table 1. A statistical analysis is undertaken considering 275 co-located samples selected from both simulated and ASCAT WS maps. As shown in Table 1, different indicators are evaluated including the root mean square error (RMSE), the bias (BI), the scatter index (SI), the regression coefficient (R) and the summary performance score (SPS). The R and SI values confirms the satisfactory performance of the numerical simulations. The positive BI (simulated WRF WS minus altimeter WS) shows that the WRF simulations overestimate the wind speed on the whole area, but this overestimation is not significant. On the whole, the statistical comparison indicates a fairly good agreement, with RMSE lower than 3 m/s standing for a remarkable results during a storm event.

In order to evidence possible systematic errors between simulated and remotely measured wind speeds depending on the geographical location, we evaluated the space distribution of the discrepancies between simulated and ASCAT WS, reported in Fig. 4.

Table 1. Statistical comparison between ASCAT-based and simulated WS. 275 independent samples are considered for the analysis.

RMSE	BI	SI	R	SPS
2.8400	0.1307	0.2427	0.5988	0.7844

Note that the sampling points are the same selected for the statistical analysis (see Table 1). The geographical distribution of the discrepancies shows an underestimation of the ASCAT WS on the southern limit of the domain, probably because of orographic complexity (presence of isles), while in the center and on the northern border the agreement is better. In particular, along the Ligurian coast mostly affected by the storm surge, the difference - in absolute value - between the two wind speeds lies below 3 m/s, witnessing the agreement between modeling simulations and satellite radar observations in this study area.

IV. DISCUSSION

The examination of Fig. 4 shows that the accuracy of the ASCAT WS is higher in the open sea (northern border of the domain) with error always lower than 3 m/s. On the contrary, where the coastal orography is more complex, the stability of the ASCAT results decreases, with an overestimation on the southern boundary. Moreover, the region of WS higher than 12 m/s is wider for WRF (Fig. 5). This is consistent with the results of Yang et al. [19], who noticed a systematic ASCAT underestimation for WS>15 m/s.

Neverthless, the whole results are encouraging particularly in the study area of the Ligurian Sea, where the accuracy is better than 3 m/s.

V. CONCLUSIONS

In this paper a further analysis of the "Vaia" storm event in the Ligurian Sea was performed, with a particular focus on the wind speed. WRF numerical simulations and ASCAT remote sensing measurements of WS were statistically compared. The whole results are encouraging in open sea, while a further effort has to be done to improve the limited temporal and spatial resolution of the ASCAT winds and the limited accuracy in presence of complex coastal orography.

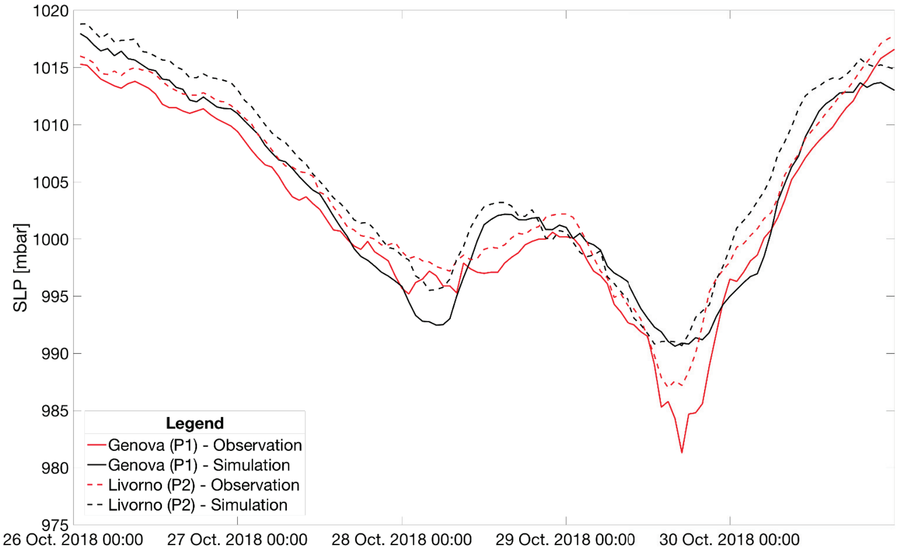

Fig. 2. Comparison between observed and simulated sea level pressure (SLP) during the period 26-30 October 2018 in P1 and P2 locations.

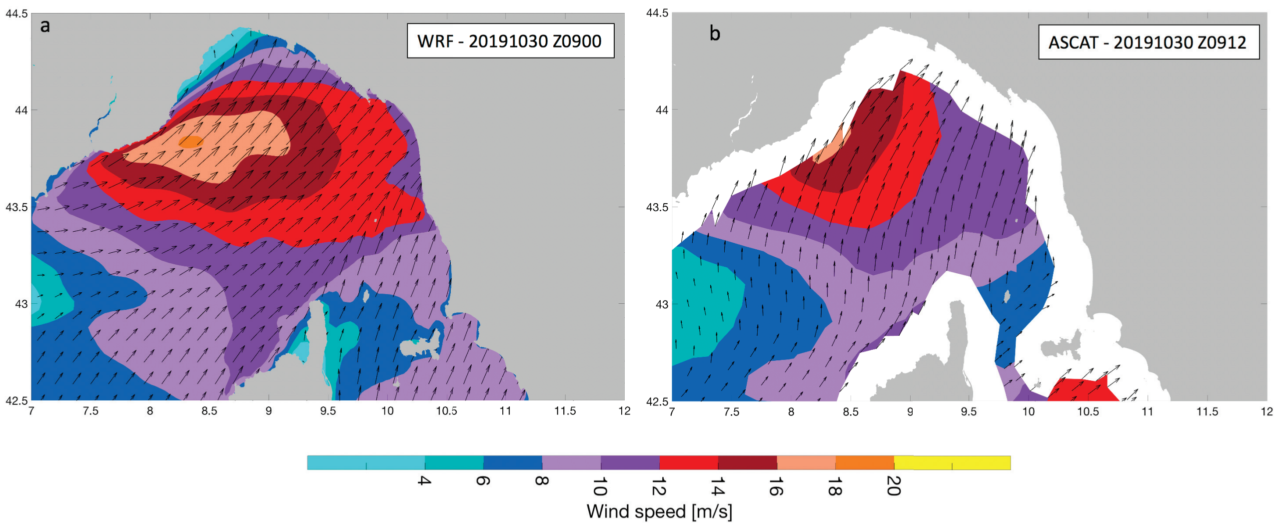

Fig. 3. WRF-based simulations versus ASCAT-based sea wind speed maps obtained over the study area during the storm event. (A) WRF 30 October 2018 at 9:00 UTC; (B) ASCAT 30 October 2018 at 9:12 UTC.

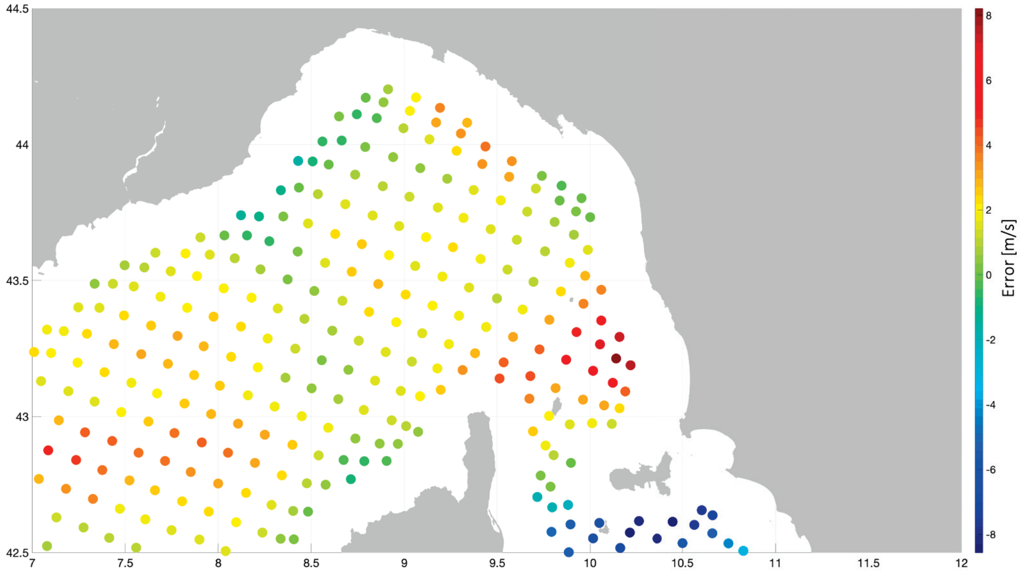

Fig. 4. Space distribution of the WRF versus ASCAT wind mismatch. The same 275 samples considered for the statistical analysis are used.

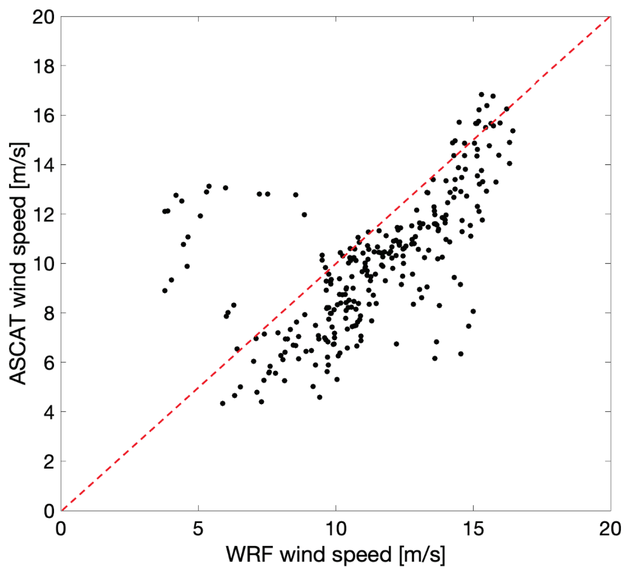

Fig. 5. Scatter diagram between WRF and ASCAT wind speed. The point far above the 45° line belong to southern border of the domain under the Elba isle.

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