IMPROVEMENTS OF STORM SURGE FORECASTING IN THE GULF OF VENICE WITH SATELLITE DATA: THE ESA DUE ESURGE-VENICE PROJECT

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ABSTRACT

The results of the re-analysis experiments conducted during the ESA eSurge-Venice project are presented and discussed. They were aimed to test the sensitivity in the Adriatic Sea of a storm surge model to a model wind forcing modified using scatterometer winds in order to reduce the differences between the statistics of the model winds and that of the scatterometer. Re-analysis experiments were also performed to test the response of the storm surge model to the assimilation, with a dual 4D-Var system, of satellite altimeter tracks as model errors of the initial state of the sea surface level. Remarkable improvements on the storm surge forecast have been obtained for what concerns the modified model wind forcing. Encouraging results have been obtained also in the assimilation experiments.

1. INTRODUCTION

The Data User Element (DUE) program of the European Space Agency (ESA) is funding two projects (eSurge and eSurge-Venice) aiming to demonstrate the improvements, on the storm surge (SS) forecasting, obtained by using Earth Observation (EO) data. Storm surges are anomalous sea level rise caused by intense meteorological conditions.

eSurge-Venice (www.esurge-venice.eu), is specifically focused on the Adriatic Sea, a semi-enclosed basin situated in the northern Mediterranean Sea and connected to it through the Strait of Otranto in the south-east (Fig. 1). This paper describes the methodologies exploiting the satellite data – principally scatterometer wind and altimeter Total Water Level Envelope (TWLE) – and the dedicated reanalysis experiments.

When the astronomical high tide and a relevant SS occur simultaneously, the high water phenomenon is likely to happen in the northern Adriatic Sea, flooding Venice and its lagoon (red mark in Fig. 1).

To prevent risks and to prepare the needed countermeasures where possible, storm surge models (SSMs) are used to forecast the sea level in the Gulf of Venice and inside the Venice Lagoon.

Present SSMs use Numerical Weather Prediction (NWP) model fields as forcing, while the sea surface level initial conditions of the forecast simulation are supplied by the SSM itself as a result of the spin-up phase. Both the accuracy of the NWP wind forcing and the quality of the sea level initial condition are important for a successful forecast of the storm surge level.

While the first issue can be tackled using satellite-borne scatterometer data, satellite altimetry is suitable to deal with the second one.

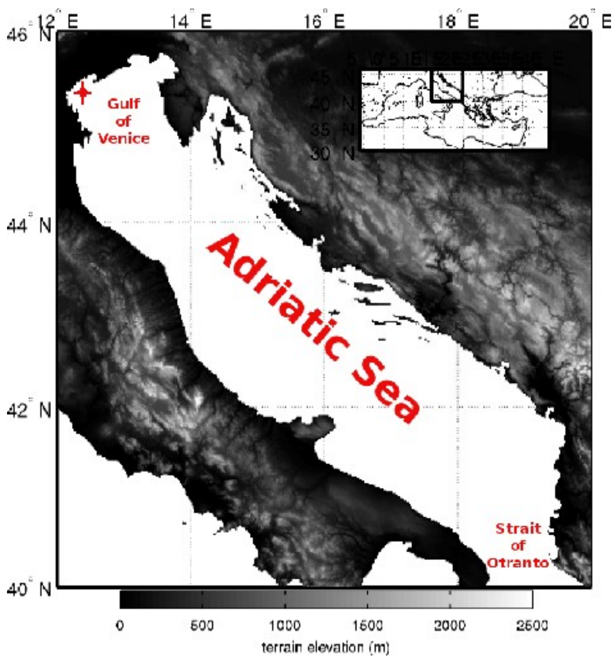

Figure 1. The Adriatic Sea, its position in the Mediterranean Sea (inset), and the surrounding orography

Considering the potential applications in operational contexts, the scatterometer wind are used to tune the modelled wind forcing the hydrodynamic model.

Altimeter TWLE could instead have a direct impact on the model initial state. We thus made attempts to directly assimilate the altimeter TWLE, after an adequate pre-processing, into the hydrodynamic model. To this end we used a dual 4DVar data assimilation method.

In this work we used the European Centre for Medium-Range Weather Forecasts (ECMWF) NWP model

fields, and the Shallow water Hydrodynamic Finite Element Model (SHYFEM).
The following sections present a brief characterisation of the SS in the Adriatic Sea, the data used in this work, the SSM employed for the reanalysis experiments and the methodologies conceived to reduce the SSM uncertainties by means of EO. Results and discussion are reported at the end.

2. STORM SURGES IN THE ADRIATIC SEA

The morphology of the Adriatic Sea, deeper in its southern part and shallower in the North, and the basin's shape, elongated, semi-enclosed and surrounded by mountain chains, favour the occurrence of intense storm surge events (SEVs), in particular during autumn and winter, and with higher elevations than in the rest of the Mediterranean Sea.
The conditions responsible for the meteorological storm surges in the Adriatic Sea are well known: a low-pressure system situated west of the Adriatic Sea causes strong wind blowing along the basin's major axis, pushing the water towards the northern closed end. This particular wind is called sirocco.

2.1. The sirocco wind

The importance of sirocco in producing SSs and flooding events in Venice is well known [1].
The sirocco, associated with the crossing of cyclones over the Mediterranean Sea, is effective in pushing the water toward the northern closed end of the Adriatic Sea.
Fig. 2 reports the mean wind field from satellite-borne scatterometer data obtained averaging the surface wind fields remotely sensed during the three days before the storm surge event occurrence of 29 March 2009, 20:00 UTC. It shows a typical pattern of the sirocco: strong south-easterly winds sweep the whole basin. Often, the sirocco blows in the southern and central parts of the basin turning from north-east (bora) in the northern basin.

2.2. The seiches

The Adriatic Sea geometry favours the setup of free oscillations, called seiches. They occur as a response to unstable conditions like a horizontal gradient in the water level due to the wind action. Their period is essentially determined by the bathymetry and the basin dimensions. The two major seiches in the Adriatic Sea have periods of 21.2 and 10.8 hours. The former is the principal one in the basin and propagates along its main dimension. The latter propagates counter-clockwise as a semi-diurnal tide. There are other seiches with lower amplitudes and periods. On average, seiches produce level displacement of 20-30 cm but can reach 60-80 cm and are progressively attenuated in 10-15 days. The periods of the two principal seiches are very close to that of the diurnal and semi-diurnal astronomical tide components, giving rise to resonance effects producing high water levels even days after a storm surge event.
Seiches occur generally in winter in the Northern Adriatic and in summer time in the Southern Adriatic.

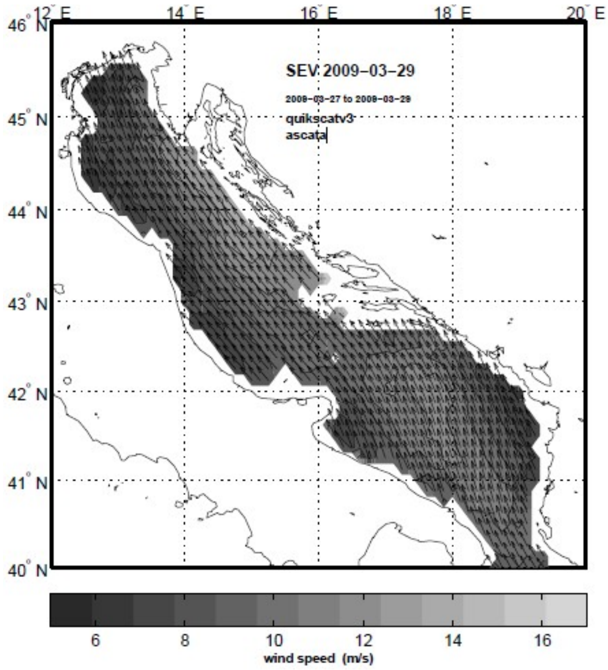

Figure 2. The mean wind field obtained from satellite observations over the three days before the storm surge event of 29 March 2009.

3. DATA

3.1. The ECMWF model data

The NWP model fields used in the project are the analysis fields of the ECMWF global model at different resolutions (from 40 km to 16 km of equivalent grid, depending on the period) interpolated on a 0.125° regular grid. The wind components at 10 m of height from the sea surface and at real air-sea stability conditions are provided at synoptic hours (00:00, 06:00.... UTC). Thus, they have been linearly interpolated to the scatterometer overpass time.
The ECMWF mean sea level pressure, air temperature at 2 m and dew temperature at 2 m analysis fields have also been used to adjust the scatterometer wind from neutral to real stability conditions.

3.2. The scatterometer wind data

The scatterometer data used in this work are the NASA QuikSCAT version 3 L2B Ocean Wind Vector (OWV) 12.5 km [2], the EUMETSAT ASCAT-A L2 OWV 12.5 km, ASCAT-A L2 Coastal OWV 12.5 km, ASCAT-B

L2 Coastal OWV 12.5 km [3] and Oceansat-2 L2B OWV 12.5 km [4]. They have been downloaded from the Physical Oceanography Distributed Active Archive Center of the Jet Propulsion Laboratory, Pasadena, USA.
Scatterometer winds, which are referenced to equivalent neutral air-sea stability conditions, have been adjusted to real stability conditions following the procedure given in [5]. The parameters needed to calculate these adjustments are the mean sea level pressure, the air and dew temperatures at 2 m and the sea surface temperature (SST). The last has been obtained from the daily sea surface temperature maps of the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system [6]. The other parameters are those of the ECMWF analysis fields already mentioned in the previous section.
Since QuikSCAT and Oceansat-2 operated at Ku-band, their data could be contaminated by rain: therefore, the data contaminated by heavy rain (very few) were discarded. Although C-band scatterometer measurements are less affected by precipitation, the Level 2 Rain Flag parameter has been used to filter the ASCAT-A and ASCAT-B data.
The scatterometer data have been interpolated on the same 0.125° regular grid used for ECMWF data with a Laplacian method which does not change the statistics of the wind speed and direction [7].

3.3. The altimeter data

The altimeter is a radar aboard a satellite that measures the distance of the sea surface from the instrument.
We used altimetry data coming from three different satellites: NASA/CNES Jason-1 (2002-2009), NASA/CNES/NOAA/EUMETSAT Jason-2 (2008-present) and ESA Envisat (2002-2010). Envisat has long repeat cycles (30-35 days) and tight ground track spacing (80 kilometres at the equator), while the other two have relatively short repeat cycle (10 days), able to observe the same spot on the ocean frequently but with relatively widely-spaced ground tracks (315 kilometres at the equator). The tracks over the Adriatic Sea cyclically re-visited by the three satellites are shown in Fig. 3.
Altimeter standard products have reduced accuracy in coastal areas and regional seas. This is the case of the Adriatic Sea, which can be considered almost entirely a coastal sea [8]. For this reason reprocessed products dedicated to the monitoring of coastal areas have been adopted. Compared to standard products they include higher along track resolution, improved re-trackers, improved corrections, refined pre-processing and post-processing. Among the agencies providing such products (COASTALT, CTOH, PISTACH) those supplied by CTOH (Center for Topographic studies of the Ocean and Hydrosphere) have been found the most suitable. CTOH provides 1-Hz (7 km) along-track mono-mission regional products (including Adriatic Sea) in delayed time, derived from the level 2 Geophysical Data Record (GDR), with specific coastal pre-processing.

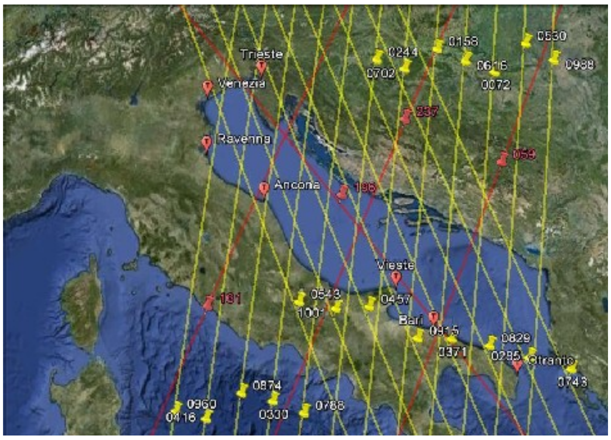

Figure 3. Ground track coverage in the Adriatic Sea. Red lines: expected crossing by Jason-1 and Jason-2. Yellow lines: expected crossing by Envisat.

The altimetry parameter used in the reanalysis experiments is the sum of the Sea Level Anomaly (SLA) and the wind and pressure correction. The sum of these quantities is also referred as the Total Water Level Envelope (TWLE) after subtraction of tides. In the following we will use the term TWLE* to indicate the de-tided TWLE.

4. THE STORM SURGE MODEL

The SHYFEM model [9] is based on the finite element discretisation technique, with a semi-implicit time stepping. In order to avoid mass conservation issues, it uses a scattered grid, with water level specified at nodes and velocities at the elements' centres.
For the present application the equations include the Coriolis, the horizontal turbulent diffusion, the bottom friction and the wind and pressure forcing terms.
Baroclinic terms and tidal forcing are not included. The equations are vertically integrated, in a 2D hydrostatic shallow water formulation, whit a third equation expressing the mass conservation.
The simulations run over a computational grid of the Mediterranean Sea. The grid size is smaller in the shallow zones and in the Adriatic Sea (up to 4 km), while increases in the central sub-basins and in deep zones in order to keep reasonable computational loads.
Open boundary conditions are assumed in the Atlantic Ocean border, where the water level is set to a null value and the water fluxes are unconstrained. The simulations are forced with surface wind and pressure, and the computed water level can be properly identified with the meteorological surge. Astronomical tide is not considered, since in the Mediterranean Sea, due to its

low amplitude, non-linear interactions with surge are negligible.

5. METHODS

In the following sections we present two applications of satellite data developed to bring the potential of EO in support to SSM forecasting.

5.1. NWP wind bias mitigation

Small basins surrounded by steep orography are known to be areas where the atmospheric modelling performances are lower than in open-ocean. In the Adriatic Sea, for example, the scatterometer-model wind bias has been found particularly dependent on time and space [10].

The scatterometer winds, however, are not suitable to be used directly as forcing in the SSMs because of the poor re-visitation period (1.5 datum/day maximum) and the irregular re-visitation time and spatial coverage. On the other hand, assimilation of scatterometer winds into NWP limited area models is still far from being an operational practice, and highly demanding to be afforded by local and regional meteorological and oceanographic agencies.

They can instead be useful in understanding and quantifying the observations-model bias, which can be used in turn to adapt the NWP wind fields for storm surge modelling applications. Preliminary investigations of differences and similarities between scatterometer and model winds have been carried out by means of the normalised wind speed bias $\Delta w^N(i,j)$, defined as:

$$\Delta w^N(i,j) = < \frac{w^{sc}(i,j) - w^e(i,j)}{w^{sc}(i,j)} > \quad (1)$$

where $w(i,j)$ is the wind speed at the location (i,j) of a grid covering the Adriatic Sea, the symbol <...> indicates the temporal average of the quantity in brackets and the superscripts *sc* and *e* refer to scatterometer and ECMWF respectively.

The wind direction bias $\Delta\theta(i,j)$, where $\theta(i,j)$ is the wind direction, is the mean difference between the scatterometer and the ECMWF wind direction:

$$\Delta\theta(i,j) = < \theta^{sc}(i,j) - \theta^e(i,j) > \quad (2)$$

The representation of the statistics of the two bias over a period of almost two years (January 2008-November 2009) is reported in Fig. 4: the left panel shows the percent bias between the two data set, always positive (ECMWF underestimates winds with respect to scatterometer), reaching the 25% along coasts; the mean bias of the wind direction, in the right panel, is less dramatic, showing differences only along coast (from -20 to 10 degrees).

The situations summarised by the two figures above are rather general, claiming for a methodology to mitigate the two bias.

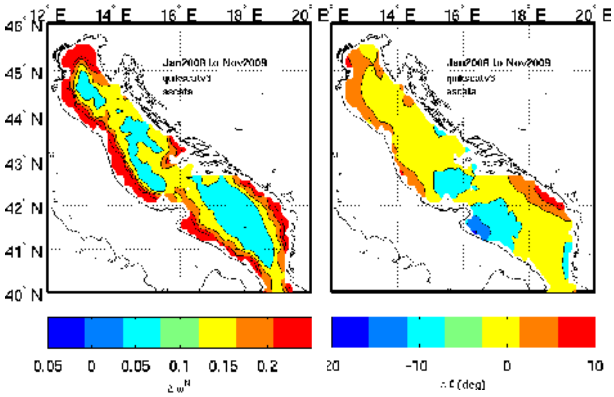

Figure 4: Scatterometer-ECMWF wind speed normalised bias (left) and wind direction bias (right) for the period January 2008 to November 2009.

The results shown above suggest to perform a tuning of the model wind to mitigate both the wind speed and the direction bias. This methodology has been first proposed and investigated in [11]. The approach for the wind speed relies on the normalised bias $\Delta w^N(i,j)$, i.e.

$$w^{e\prime}(i,j) = w^e(i,j) * (1 + \Delta w^N(i,j)) \quad (3)$$

while that for the wind direction simply relies on $\Delta\theta(i,j)$, i.e

$$\theta^{e\prime}(i,j) = \theta^e(i,j) - \Delta\theta(i,j) \quad (4)$$

where the prime symbol marks the bias-mitigated variables. From the operational point of view, the normalised wind speed bias and the wind direction bias, calculated over a running observation window of three days, are applied to calculate the mitigated NWP wind fields of the day following the observation window. The mitigation procedure has then been applied to the analysis of the fourth days, and the reanalysis experiments have been conducted considering the standard (reference) and the mitigated analysis fields of the fourth days.

This procedure can have a statistical significance only if the sample on which the biases are calculated is large enough. However, enlarging arbitrarily the observation window would turn to a loss in correlation between observations pertaining to different meteorological phenomena falling whitin the window, and thus to a reduction of the statistical significance. The period chosen to compute the biases is of three days before the

SS occurrence, estimated from the mean duration of the sirocco wind in the Adriatic Sea. In Fig. 5 are shown the ECMWF model wind speed normalised bias and wind direction bias for a the Storm Surge Event (SEV) of the 03/29/2009, before the application of the bias mitigation technique (left), and after mitigation (right). White areas are for values of Δw^N in the range (-5%, +5%). It is easily seen that after mitigation the areas in this range of relative wind speed bias have significantly increased, thus diminishing the bias between the model wind and the scatterometer observations both locally and globally.

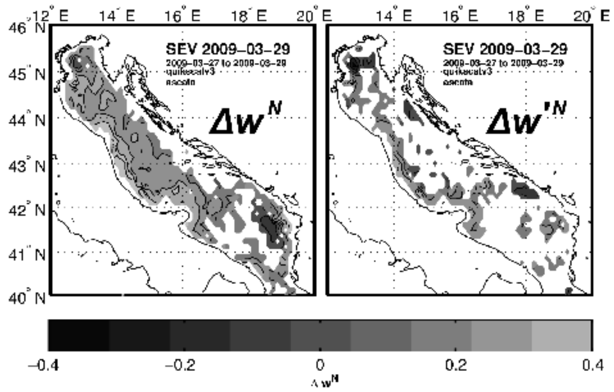

Figure 5. Δw^N for the three days before the occurrence of storm surge event of the 29-03-2009. Left panel: from the ECMWF fields. Right panel: from the ECMWF bias-mitigated fields. White areas are for $-0.05 < \Delta w^N < 0.05$.

5.2. *Altimeter data assimilation*

Altimeter records are too noisy to be directly assimilated into the SHYFEM SSM. In Fig. 6 two examples of altimeter TWLE* and SSM profiles along the altimeter ground track are shown. The left panel shows an example of how the model background state misrepresents the observed TWLE* profile, while the left panel reports a case where the model and the altimeter profiles are rather well correlated, apart from the very high frequency contained into the altimeter TWLE*.

A non-linear fit was used to obtain smoother spatial signals, with a characteristic length scale near to the actual spatial resolution of the SSM. The differences between this signal and the modelled surge were assimilated, after subtracting the minimum distance between the two signals, with a dual form of 4-Dimensional Variational (4D-Var) data assimilation based on the Physical-space Statistical Analysis System (PSAS) algorithm (4D-PSAS) [12].

This technique is used with the aim of correcting the background state of the modelled sea state before the forecast run. As such, only the altimeter tracks crossing the Adriatic Sea the day before the SEV can be assimilated. As a matter of fact, the scarcity of altimeter passages in the (very narrow basin of) Adriatic Sea makes the assimilation impracticable in some cases.

Due to the lack of a common terrestrial reference frame, the altimetric TWLE* (which is referred to the ellipsoid) and the surge level simulated by SSMs (which is referenced to the geoid, roughly known in the Adriatic Sea) cannot be compared directly. However, their profiles should have comparable shapes, up to an additive constant, thus permitting the assimilation into SSMs of their differences as model errors.

Moreover, the altimeter TWLE* contains components due to baroclinic terms and low frequency atmospheric forcing, which are not reproduced by the SSM. Due to these components and to the fact that the water level is referred to the ellipsoid, the altimeter mean sea level differ from the modelled one, which is referred to the local tide gauge mean sea level. This is the origin of the additive constant mentioned in the previous paragraph.

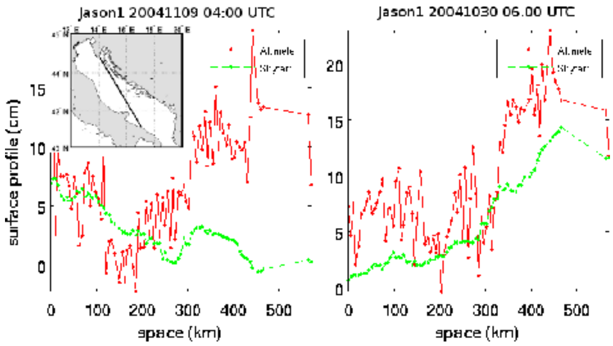

Figure 6: Two examples of Jason-1 altimeter track profiles over the Adriatic Sea. Left panel: 09-11-2004 04:00 UTC. Right panel: 30-10-2004 06:00 UTC. The TWLE (red) and SSM background state (green) profiles along the altimeter ground track are plotted. The inset shows the altimeter track in the Adriatic Sea, the same for both examples.*

6. RESULTS

6.1. *The reanalysis scheme*

The re-analysis experiments have been carried out on 22 SEVs from 2004 to 2012 (Tab. 1). For each SEV, first a numerical simulations was started 20 days before the SEV's day, in order to avoid model spin-up issues, and finished 10 days after. The model sea surface level one day before the SEV occurrence was used as initial condition for further model runs.

Four re-analysis experiments have been performed, and the corresponding simulation sets are marked with the following labels:

- REF: standard wind, no TWLE* assimilation;
- SCATT: mitigated wind, no TWLE* assimilation;
- ALT: standard wind, TWLE* assimilation;
- SCATT+ALT: mitigated wind, TWLE* assimilation.

The REF simulations are the reference forecasts against

which the other simulations are compared. from which the performance of the re-analysis experiments are evaluated.
The analysis of the modeled surge is made at the oceanographic platform Acqua Alta, located in the northern Adriatic Sea, 15 km off-shore the Venice coast, where good quality tide gauge data are available. The tidal signal is removed from observations by means of harmonic analysis. The observed surge can be compared directly to the modeled surge after a correction of the mean sea level (non-linear interactions are negligible).

Table 1. Re-analysis SEV dates

2004	10/31	11/10	12/26			
2005	12/03					
2008	12/01	12/10				
2009	01/26	02/02	03/29	11/30	12/19	12/22
2010	01/07	02/28	11/10	11/19	11/26	
2011	02/16					
2012	10/27	10/31	11/11	11/28		

Four SEVs have no TWLE* records in the assimilation time window: for them only the wind bias mitigation is evaluated.
The experiments results are analysed in terms of the values of the observed maximum peak values and the corresponding modelled peaks, irrespective of the time lag between the two peaks inside a complete tidal cycle (12 hours for spring tides), of their differences (skew differences) and of their RMS difference.

6.2. *The REF run situation*

The reference situation against which the other experiments will be compared is shown in Fig. 7. It is the plot of the absolute skew difference values for the 22 SEVs, using the using as forcing in the SSM runs the

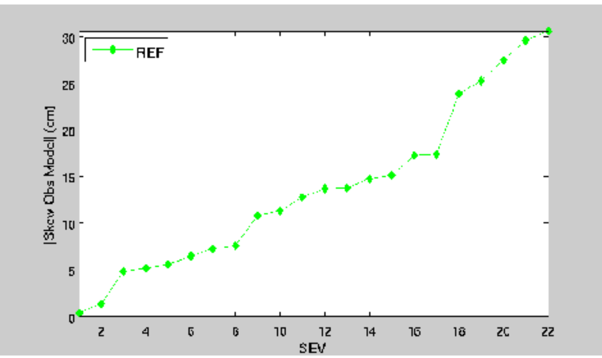

Figure 7. Absolute skew differences of the observed and modeled surge peaks for all the SEV, ordered by increasing values.

standard analysis fields of the ECMWM global model. The general trend is an underestimation of the observed surges, with absolute skew differences ranging from few cm to 30 cm with a rather uniform distribution of the difference values. Looking at the results of the other experiments, reported in Fig. 8, we see that in very few cases the other three experiments give worse results than the reference simulation.

6.3. *SCATT experiment results*

In the SCATT experiment, the absolute values of the skew differences from the simulations obtained using the tuned ECMWF data (SCATT, in red in Fig. 8) are in general lower than those from the standard ECMWF data (REF, in green). Since the wind speed is generally increased by the bias mitigation technique, the use of SCATT ECMWF winds improves the SEVs for which the SSM level was underestimated, while worsens the few SEVs overestimated. With the SCATT winds only 6 SEVs show a relative bias greater than ± 10%, which is a remarkable result. The RMS difference of all the SEVs decreases from 16.3 cm (REF) to 10.2 cm (SCATT).

6.4. *ALT experiment results*

The assimilation of altimeter TWLE* into the SHYFEM SSM has been done for eighteen SEVs, because of lack of suitable altimeter tracks for 4 of the 22 SEVs. The absolute skew differences for the ALT experiment are

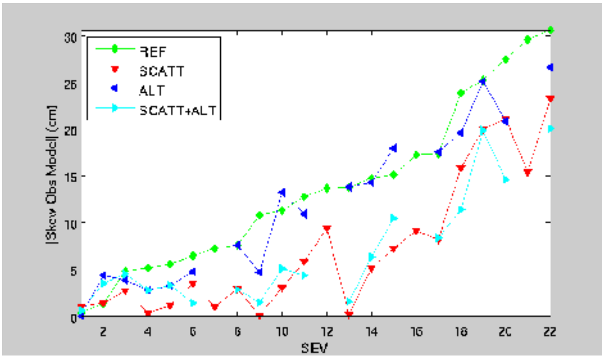

Figure 8. Summary of the results obtained by the re-analysis experiments. The SEVs have been ordered by increasing size of the modulus of the Obs-model absolute skew differences of the REF simulation.

plotted in blue in Fig. 8. The assimilation of the altimeter TWLE* into the hydrodynamic model does not seem to bring results as relevant as those obtained in the SCATT experiment. Nevertheless the RMS difference slightly decreases from 16.3 cm to 14.2 cm, indicating a modest but positive impact of TWLE* assimilation in the SSM.

6.5. *SCATT+ALT experiment results*

In the SCATT+ALT experiment (cyan marks in Fig. 8) the modest but positive impact of TWLE* assimilation determines a further reduction of the RMS difference compared to the already good results of the SCATT experiment. Of course, the main improvements are brought by the SCATT, according to the results presented above. The RMS differences decreases from 16.3 cm to 9.0 cm.

6.6. Overall considerations

The simulations with the wind correction (SCATT) show a pretty uniform performance. The real wind is almost always underestimated in the Adriatic Sea in case of an extreme event. This type of correction does not alter in general the phase of the surge, but increases the positive peaks. Moreover, in the 22 cases considered, it never worsen the forecast.

The best simulation set is that with both the corrections (SCATT+ALT), even though, in some cases, the simulations with just the wind correction (SCATT) is slightly better. This happens when the altimeter data have low quality or even when the scatterometer increases too much the surge, since the two contributions, SCATT and ALT, have the tendency to add up.

Moreover, SCATT simulations keep a better resemblance (not shown) with the original forecast (REF) than the altimeter ones (ALT and SCATT+ALT), but decreasing the scatterometer-model differences. The simulations with altimeter assimilation (ALT and SCATT+ALT) sometimes causes a time shift of the surge curve and a more radical change of its shape, adding artefacts around the assimilation window time (not shown).

7. DISCUSSION

The wind bias mitigation methodology takes the scatterometer wind as the reference to adjust the ECMWF forecast winds. This has been required by the known underestimation of ECMWF winds in the Mediterranean Sea [13]. Similar biases have been found in the Adriatic Sea. The characteristics of these biases do not seem to be peculiar to the ECMWF global model which, in our opinion, is of outstanding quality.

Another issue is the inter-comparison between different scatterometer data. In the present work we have used QuikSCAT, Oceansat-2, ASCAT-A and ASCAT-B data. According to [14], the bias between the QuikSCAT and ASCAT-A data sets on a worldwide analysis is lower than 1 m/s, with several spatial differences. From an independent study conducted by us about the period of QuikSCAT and ASCAT-A overlapping (March to November 2009), the bias in the Mediterranean Sea resulted almost negligible (0.6 m/s). The bias of the other datasets have not been investigated, and will form the object of forthcoming studies.

The reliability of the method depends strictly from the number of scatterometer re-visit in the area of interest. Some periods during this study were characterised by the highest temporal sampling of the Adriatic, ≈ 2 swaths per day by QuikSCAT and, during the period when QuikSCAT and ASCAT-A flew together, ≈ 3 swaths per day. Two data per day is seen here as the minimum temporal sampling to get maps of Δw^N and $\Delta\theta$ with some statistical significance, also considering the time length of the SS occurrence. In this respect, we believe that the proposed method cannot be applied using only ASCAT-A and ASCAT-B data in the present configuration, since they provide about 1 swath per day each but with a too low time separation (50 minutes lag).

Being the first attempt to assimilate altimeter data into a SSM, we believe that the results obtained in the ALT and SCATT+ALT re-analysis experiments are very promising, even if the overall impact of assimilation, with respect to bias mitigation, is low.

Apart from the complexity of the model assimilation set-up, other issues prevent the full exploitation of the method: first of all, only the altimeter tracks falling within the day before each SEV are assimilated. Those falling outside would require to enlarge the assimilation window. In this case, even though a higher number of data would be available, the correction to the initial state would be too far from the event to have a significant influence. A rather interesting approach would be, instead, to extend the assimilation to the whole Mediterranean Sea, because this would significantly increase the number of tracks within the assimilation period. In this respect the assimilation of tide gauges data together with altimeter TWLE* should further improve the impact of the method.

Unfortunately, even if other and more complex assimilation experiments became feasible, their impact at the operational level would remain limited, given the accuracy needed in this type of application (cm) and the consequent long delays for data distribution (weeks to months). As such, assimilation of altimetric measurements for SSM applications in the Adriatic Sea cannot be considered an operational option at present.

Overall, the re-analysis experiments conducted have shown a remarkable impact of EO data into SSM forecast. The synergy between the bias mitigation and the altimeter assimilation in the reduction of the error may be probably ascribed to the different sources of error they act on, which are the forcing wind and the initial state.

The two methods analysed showed good potential. While the altimeter assimilation can be improved in two main directions, that are the quantity of the data and their quality, the wind tuning can be further developed working on the computation of the coefficient, even adopting least squares based regression analysis techniques, and should be tested with forecast wind fields, even though we expect similar results with one day forecast fields. However it can be considered almost ready to be applied in an operational context.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. Tomasin, A. & Frassetto, R. (1979). Cyclogenesis and forecast of dramatic water elevations in Venice. In *Marine Forecasting,* Elsevier, Amsterdam, NL, pp 427–437.

2. JPL, (2013). QuikSCAT Level 2B Version 3 Guide Document. Tech. Rep. v1, March 2013.

3. OSISAF, (2012). ASCAT Wind Product User Manual (Ver. 1.12). Tech. Rep. SAF/OSI/CDOP/KNMI/TEC/MA/126, Eumetsat, Darmstadt, Germany, August 2012.

4. JPL, (2013). Oceansat-2 Level 2B User Guide Guide Document. Tech. Rep. v1, February 2013.

5. Liu, W.T., Katsaros, K.B. & Businger, J.A. (1979). Bulk parameterization of air–sea exchange of heat and water vapor including the molecular constraints at the interface. *J. Atmos. Sci*. **36**, 1722–1735.

6. Stark, J.D., Donlon, C.J., Martin, M.J. & McCulloch, M.E. (2007). OSTIA: An operational, high resolution, real time, global sea surface temperature analysis system. In: Oceans 2007. IEEE, Aberdeen, Scotland, UK.

7. Accadia, C., Zecchetto, S., Lavagnini, A. & Speranza, A. (2007). Comparison of 10-m Wind Forecasts from a Regional Area Model and QuikSCAT Scatterometer Wind Observations over the Mediterranean Sea. *Monthly Weather Review*, **135**, 1946–1960.

8. Zecchetto, S., De Biasio, F. & Accadia, C. (2012). Scatterometer and ECMWF-derived wind vorticity over the Mediterranean Basin. *Q. J. R. Meteorol. Soc.,* **139**, 674–684.

9. Umgiesser, G., Melaku Canu, D., Cucco, A. & Solidoro, C. (2004). A finite element model for the Venice Lagoon. Development, set up, calibration and validation. *Journal of Marine Systems*, **51**, 123–145.

10. Zecchetto, S. & Accadia, C. (2014). Diagnostics of T1279 ECMWF analysis winds in the Mediterranean Basin by comparison with ASCAT 12.5 km winds. .*Q. J. R. Meteorol. Soc.*

11. Zecchetto, S., della Valle, A. & De Biasio, F. (2014). Mitigation of ECMWF-scatterometer wind biases in view of storm surge applications in the Adriatic Sea. Submitted to *Advances in Space Research*.

12. Courtier, P. (1997). Dual formulation of four-dimensional variational assimilation. *Q.J.R.Meteorol.Soc.*, **123**, 2449–2461.

13. Zecchetto, S. & De Biasio, F. (2007). Sea surface winds over the Mediterranean Basin from satellite data (2000-2004): meso- and local-scale features on annual and seasonal timescales. *Journal of Applied Meteorology and Climatology.* **46**(6), 814–827.

14. Bentamy, A., Grodsky, S.A., Carton, J.A., Croizé-Fillon, D. & Chapron, B. (2012). Matching ASCAT and QuikSCAT winds. *Journal of Geophysical Research.* **117**, C02011.