Sea surface model wind bias reduction with satellite scatterometer observations

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INTRODUCTION

Coastal areas are exposed flooding caused by storm surges. The Gulf of Venice, in the Adriatic Sea (northern Mediterranean Sea), is particularly prone to this phenomenon. National and local agencies run operational storm surge models to alarm the population and mitigate the impact of flooding. The storm surge model atmospheric forcing is supplied by atmospheric models, whose performance in coastal areas is generally lower than in open-ocean: in the Adriatic Sea the surface wind forecasts are often underestimated *[Zecchetto and Accadia, 2014]*.
We propose a numerical method to reduce the bias between the sea surface wind observed by the scatterometers and that supplied by numerical weather prediction (NWP) models, for storm surge forecasting applications.

THE PROBLEM

The quality of the atmospheric forcing determines the accuracy of the storm surge model simulation, as the surge elevation depends on the wind stress, which is proportional to the squared wind speed. ***In Fig. 1 is reported the relative bias spatial pattern (∆ws) for scatterometer-model data for two years (Jan 2008 - Nov 2009) in the Adriatic Sea: it ranges from -5% to +20% of the scatterometer wind*** [Zecchetto et al., 2015]. A bias is found also in the wind direction: it will not be considered here. Also shown in Fig. 2 the global distributions of wind speed and direction between scatt and model.

Scatterometer observations form QuikSCAT and ASCAT
NWP model data form the global deterministic model of ECMWF

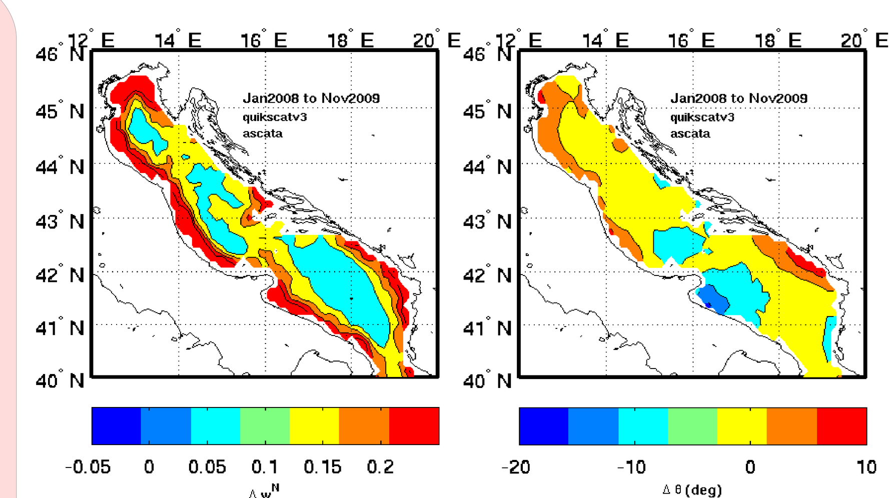

Fig. 1 - SCATT-ECMWF bias spatial pattern Jan 2008 - Nov 2009. Left: relative wind speed bias; right: wind direction bias.

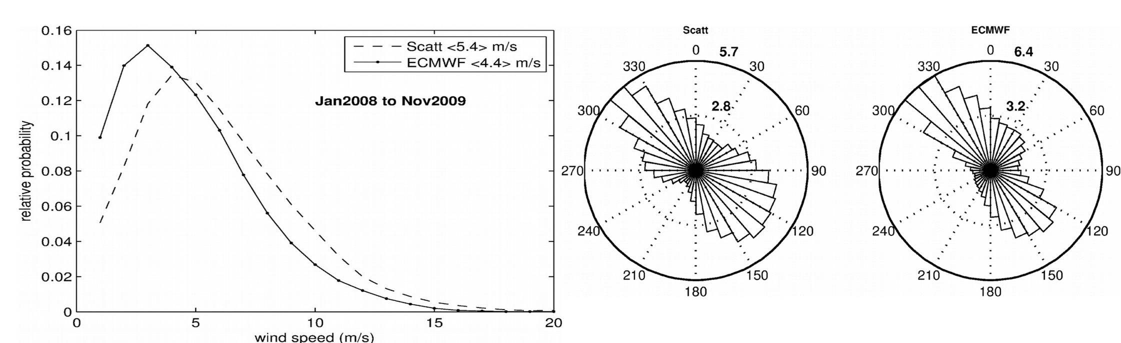

Fig. 2 - Distributions of wind speed and direction frequencies for scatterometer and ECMWF model (Jan 2008 – Nov 2009): ECMWF wind speeds are generally lower than scatterometer observations (bias ≈ 1 m/s). ECMWF has narrower direction distributions directed N-S.

PROPOSED SOLUTION: WIND BIAS MITIGATION

Today satellite scatterometers provide accurate observations of the sea surface wind: they can be used to estimate and mitigate the wind speed bias of the atmospheric models. ***Model winds are scaled by a local factor (1+∆ws)***, where ∆ws is a function of past model and satellite wind data at each location (**see Box 1 to your right ►►**). ***We compare four different mathematical approaches to this method, for a total of eight different formulations of the multiplicative factor ∆ws:***

1. Original formulation of the wind bias mitigation (**OF: Box 2 ►►**)
2. Alternative formulations of the OF (**AF1&AF2: Box 3 ►►**)
3. Analytical solution (**AS: Box 4 ►►**)
4. Least square regression (LSR) approach

- Linear least squares regression (**LLSR & LLSR$_E$: Box 5 ►►**)
- Relative least squares regression (**RLSR & RLSR$_E$: Box 6 ►►**)

VERIFICATION

Four datasets are used for the assessment of the eight different bias mitigation methods:

- 29 Storm Surge Events (SEVs) cases in the years 2004-2014
- 48 SEVs in the years 2013-2016
- 364 cases of random sea level conditions in the same period
- The 7 SEVs in 2012-2016 that were worst predicted by the Venice Tide Centre of the Venice Municipality.

We found that the standard model forecast and the eight mitigated model forecast winds, compared with scatterometer observations, over the whole set of four datasets:

- Have similar centered RMS difference (scatt – model) (**Fig. 3 below**)
- **Have comparable Pearson's correlation** (**Fig. 3**)
- Have similar standard deviation (**Fig. 3**)

Moreover:

- The mitigated forecasts perform better than the standard forecast in about 70 % of the cases (**Table 1**)
- **The mitigated forecasts have always a lower bias than the standard forecast** (**Table 2**)

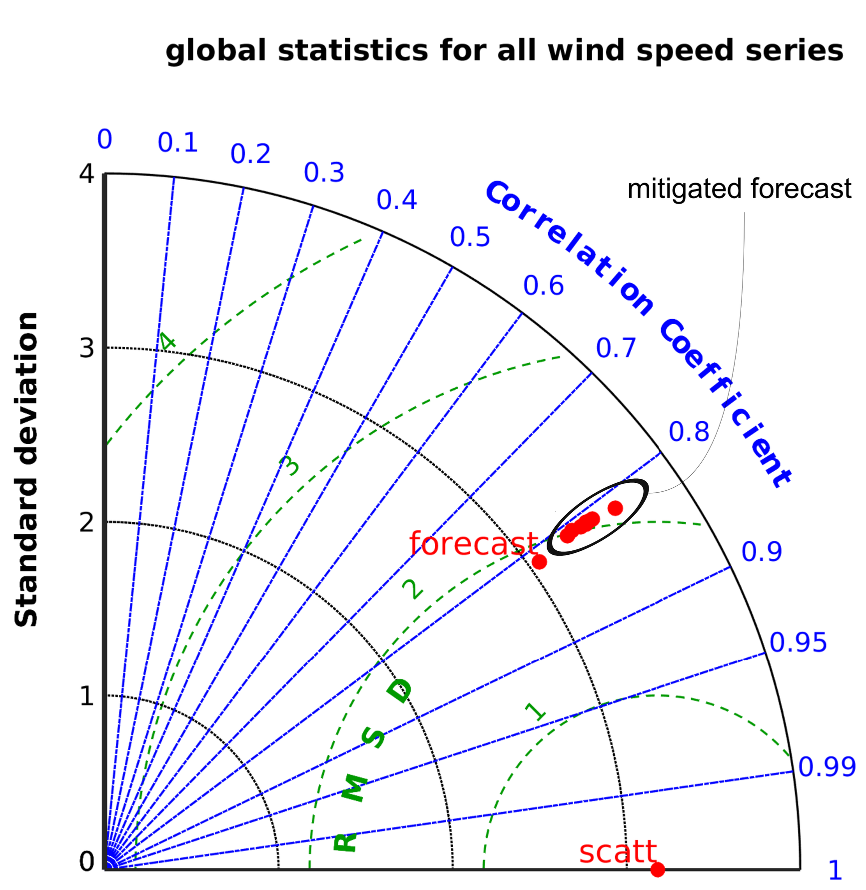

Fig. 3 - Taylor diagram showing the statistical results for the D3 dataset. The centered RMS differences, the Pearson's correlation coefficients and the standard deviations of the original (forecast) and of the **mitigated forecast** are compared to scatterometer observations taken as a reference (scatt). The position of the mitigated forecast values for **the eight different WBM types are clustered close to the position of the original forecast**.

Dataset	LLSR	RLSR	OF	AF1	AF2	AS	LLSR$_E$	RLSR$_E$
D1 (#29)	79	72	72	76	76	76	79	76
D2 (#48)	79	73	73	71	75	75	81	75
D3 (#364)	71	71	73	71	73	73	73	70
D4 (#7)	86	71	86	57	86	86	100	86

Table 1 - Percentage of success (POS): percentage of times that the RMS difference of the means of the mitigated winds and of the scatterometer means resulted lower than the RMS difference of the standard forecast means and those of the observations. POS are shown for four datsets and the eight mitigation types. **The WBM procedure performs better than the forecast in a percentage of cases that ranges from 70% to 100%. The best scores are obtained by the LLSR$_E$ WBM approach.**

Dataset	Original forecast	LLSR	RLSR	OF	AF1	AF2	AS	LLSR$_E$	RLSR$_E$
D1 (#29)	1.00	0.60	0.63	0.60	0.67	0.61	0.61	0.61	0.68
D2 (#48)	0.91	0.54	0.59	0.56	0.61	0.57	0.57	0.53	0.59
D3 (#364)	0.82	0.56	0.59	0.56	0.54	0.55	0.55	0.58	0.63
D4 (#7)	0.78	0.39	0.37	0.43	0.51	0.43	0.43	0.38	0.37

Table 2 - Wind speed bias of the original and the mitigated forecasts for the four datasets (m/s).

FUTURE INVESTIGATIONS ARE NEEDED:

- to analyze the performance in other spatial regions
- to assess the possible causes that determine the failure of the method in almost the 25% of the cases
- about the wind direction bias: wind speed and wind direction biases are completely independent, but they should be reduced simoultaneously, using a linear least square regression approach. The starting point is to write a cost function (CF) to be minimized, of the type:

$$CF=\sum_{i=1}^{N}\left(u_i^{scatt}-(1+\alpha)\cdot u_i^{model}\right)^2+\sum_{i=1}^{N}\left(v_i^{scatt}-(1+\beta)\cdot v_i^{model}\right)^2-\lambda\cdot\sum_{i=1}^{N}\left(\sqrt{(u_i^{scatt})^2+(v_i^{scatt})^2}-\sqrt{((1+\alpha)\cdot u_i^{model})^2+((1+\beta)\cdot v_i^{model})^2}\right)^2$$

where the optimal values of the two parameters α and β are determined at the same time, constrained by the condition on the wind speed (the factor of the Lagrange multiplier λ)

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Explanatory __BOXES__, BIBLIOGRAPHY & ACKNOWLEDGEMENTS

Box 1 - THE WIND BIAS MITIGATION [Zecchetto et al. 2015]

The mean scatt-model wind speed relative bias Δws^N is computed over a 3-day window (**DAY -3**, **-2** and **-1**) before the day of forecast (DAY 0) (the mean is over time), for each point *(i,j)* of the spatial grid.

$$\Delta ws^N(i,j) = \left\langle \frac{ws(i,j)_{scatt} - ws(i,j)_{model}}{ws(i,j)_{scatt}} \right\rangle$$

The bias is used to modify the model forecast wind of the **DAY 0**.

$$ws_{model}^{modified}(i,j) = ws_{model}(i,j) \cdot \left(1 + \Delta ws^N(i,j)\right)$$

At the end of **DAY -1** or beginning of **DAY 0** the storm surge model is forced with the modified NWP wind field to obtain surge forecast for **DAY 0**.

Box 2 - Original formulation of the wind bias mitigation (OF)

The original formulation (OF) of the model wind speed correction factor (1+Δws) [Zecchetto et al., 2015] was weakly defined, as it could occasionally take also negative values. Omitting the spatial indexes (i,j) its form is derived considering the relative bias itself as the correction factor:

$$(1 + \Delta ws) = 2 - \frac{1}{N} \sum_{k=1}^{N} \frac{ws(t_k)_{model}}{ws(t_k)_{scatt}}$$

Box 3 - Alternative formulations of the OF (AF1&AF2)

To correct the bad behaviour of the OF (Box 2), two alternative formulations of the correction factor have been introduced (AF1 and AF2):

$$\Delta ws^N = \left\langle \frac{ws_{scatt} - ws_{model}}{ws_{model}} \right\rangle \qquad \Delta ws^N = \left\langle \frac{ws_{scatt} - ws_{model}}{\frac{ws_{model} + ws_{scatt}}{2}} \right\rangle$$

They differ for the denominator: AF1 has the model wind speed instead of the scatterometer wind speed, AF2 has the mean of scatt and model wind speed.

Box 4 - Analytical solution (AS)

The analitycal solution is found imposing that exists *α* real such that $ws_{model}^{mitigated} = (1+\alpha)\, ws_{model}$ satisfies the condition:

$$\Delta ws^{N,mitigated} = \left\langle \frac{ws_{scatt} - ws_{model}^{mitigated}}{ws_{scatt}} \right\rangle = 0$$

This equation determines the form of *α*:

$$(1+\alpha) = \frac{1}{(1 - \Delta ws^N)}$$

Box 5 - Linear least squares regression (LLSR & LLSR$_E$)

The Linear Least Square Regression (LLSR) approach is intended to supply optimal solutions to the bias-mitigation factor for the model wind speed, expressed by the functional form:

$$ws(t_k)_{model}^{bias\text{-}mitigated} = (1+\alpha) \cdot ws(t_k)_{model}$$

We investigated two cost functions to be minimized:

- the classical sum of squared differences (Δα) of the scatterometer and model wind speed (LLSR):
$$\Delta_\alpha = \sum_{k=1}^{N} \left(ws(t_k)_{scatt} - ws(t_k)_{model}^{mitigated}\right)^2$$
- the sum of squared differences *of the squared scatterometer and model wind speed* (LLSR$_E$):
$$\Delta_\alpha = \sum_{k=1}^{N} \left(ws^2(t_k)_{scatt} - ws^2(t_k)_{model}^{mitigated}\right)^2$$

Box 6 - Relative least squares regression (RLSR & RLSR$_E$)

The Relative Least Squares Regression (RLSR) approach is similar to the LLSR, but the CF to be minimized is expressed as a relative quantity [Tofallis, 2008] . The two relative CF investigated are:

- the classical sum of squared differences of the scatterometer and model wind speed, relative to the scatterometer wind speed (RLSR):
$$\Delta_\alpha = \sum_{k=1}^{N} \left(\frac{ws(t_k)_{scatt} - ws(t_k)_{model}^{mitigated}}{ws(t_k)_{scatt}}\right)^2$$
- the sum of squared differences of the squared scatterometer and model wind speed, relative to the scatterometer wind speed (RLSR$_E$):
$$\Delta_\alpha = \sum_{k=1}^{N} \left(\frac{ws^2(t_k)_{scatt} - ws^2(t_k)_{model}^{mitigated}}{ws(t_k)_{scatt}}\right)^2$$

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