eSurge esa

Lessons learned assimilating EO data in Venice

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eSurge venice

Lesson Outline

- Esurge Venice: the project and the partners;
- Storm surges in Venice;
- The EO products;
- Wind tuning using scatterometer data;
- Data assimilation: a short introduction;
- Example: assimilation of tide gauge data;
- Assimilation of altimeter data: possible benefits and issues;
- Summary.

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eSurge Venice

eSurge-Venice (ESA Storm Surge for Venice) is a project funded by the European Space Agency, part of its Data User Element (DUE) programme. It aims to increase the usage of Earth Observation (EO) satellite data, within the storm surge community.

http://www.esurge-venice.eu

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Esurge Venice Partners

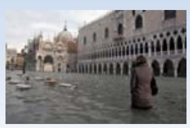
- Institute of Atmospheric Sciences and Climate (ISAC-CNR);
- Institute of Marine Sciences (ISMAR-CNR);
- Biophysics Institute (IBF-CNR);
- Institution Centro Previsioni e Segnalazioni Maree (ICPSM).

Storm surges in Venice

Total sea level	Flooded part
190 cm	88%
140 cm	59%
130 cm	46%
120 cm	28%
110 cm	12%
100 cm	5%

Sea level over 110 cm

Groundwater extraction



Operational storm surge models in Venice Statistical models

Statistical models

Based on linear regression, they are still the most used to forecast the sea level in Venice.

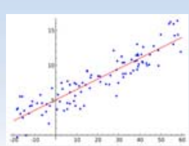
Predictors can be tide gauge data, msl pressure data or their gradients, measured wind, model forecast data (wind and pressure), etc.

Residual error

$$y_i = a_1 x_{1i} + a_2 x_{2i} + \dots + a_n x_{ni} + \varepsilon_i$$

Predictors

Calibration coeff



Operational storm surge models in Venice
Statistical models

The good:
- Very accurate in the short term forecast (6-12 hours)

The bad:
- Difficult to find the best predictors;
- Limited number of predictors;
- Possible calibration problems (overfitting);
- Extreme events' database is short.
- ...

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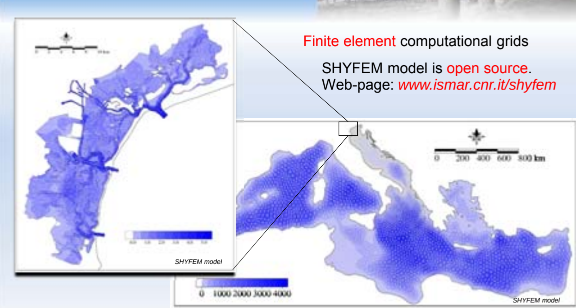
Operational storm surge models in Venice
Deterministic model



Finite element computational grids

SHYFEM model is open source.
Web-page: *www.ismar.cnr.it/shyfem*

Operational storm surge models in Venice
Deterministic model

Shallow water equations

$$\frac{\partial U}{\partial t} - fV = -H\left[g\frac{\partial \zeta}{\partial x} + \frac{1}{\rho_0}\frac{\partial p_a}{\partial x}\right] + A_H \Delta U + \frac{1}{\rho_0}\left(\tau_{wx} - \tau_{bx}\right)$$

$$\frac{\partial V}{\partial t} + fU = -H\left[g\frac{\partial \zeta}{\partial y} + \frac{1}{\rho_0}\frac{\partial p_a}{\partial y}\right] + A_H \Delta V + \frac{1}{\rho_0}\left(\tau_{wy} - \tau_{by}\right)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$$

Operational storm surge models in Venice
Deterministic model

Shallow water equations

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Inverse Barometric Effect (IBE)

Wind stress

Operational storm surge models in Venice
Deterministic model

Total sea level ~= surge + tide + bias

Astronomical Tide

If tide-surge non-linear interactions are small the two contributions can be considered linearly independent

→ Tide can be computed for a specific location from the sea level observations, by means of harmonic analysis

Operational storm surge models in Venice Deterministic model

Total sea level ~= surge + tide + bias

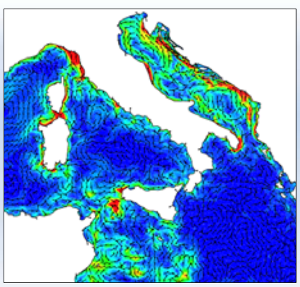
Bias

- Due to circulation induced by both average wind-pressure forcing and baroclinic forcing (low frequency oscillations ~>2-3 days);
- Only partially reproduced by the model;
- Can be corrected using the mean sea level recorded in the latest days.

Operational storm surge models in Venice Deterministic model

The good:
- Good accuracy in medium-long range forecasts;
- no need of a database of parameters correlated to storm surge;
- Automatically improves when atmospheric forecast improves;

The bad:
- Less accurate for short range forecasts (<6h);
- Difficult to correct if the atmospheric forecast is wrong;
- Higher computational times.



EO data

The spatial extension of EO data makes them very suitable to be used with deterministic models. Their use in statistic models is more difficult.

SCATTEROMETER DATA to improve **the wind forecast** used to force the model.

ALTIMETER DATA to improve the **initial state** of the model.

EO data scatterometer

Winds in the Adriatic Sea are underestimated by atmospheric models, due mainly to the complicate orography of the geographical area.

CNR Platform – 10m wind – year 2008

EO data scatterometer

We considered 12 Storm Surge Events (SEVs) happened in Venice. The highest in the last years.

- SEV 2010-02-28
- SEV 2010-11-10
- SEV 2010-11-19
- SEV 2010-11-21
- SEV 2010-11-26
- SEV 2010-12-23
- SEV 2011-02-16
- SEV 2012-10-27
- SEV 2012-10-31
- SEV 2012-11-02
- SEV 2012-11-11
- SEV 2012-11-28

EO data wind tuning

- ECMWF wind speed (w_e) was tuned using scatterometer wind speed (w_s);
- These quantities were *averaged over a specific temporal window* around each SEV;
- A similar procedure was followed for directions, $\Delta\theta$.

$$w_c = w_e + (w_s - w_e/w_s)\, w_e$$
$$\theta_c = \theta_e + \Delta\theta$$

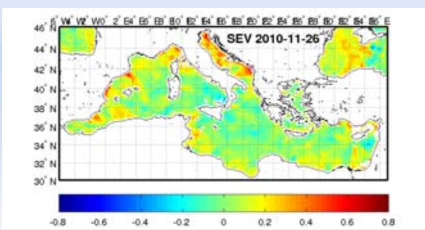
EO data wind tuning

Wind stress

The wind stress have been computed using a boundary layer model derived from Liu et al. (1979). The necessary bulk quantities input to the model are the SST, the dry and wet air temperatures, and the atmospheric pressure at the sea level. While the SST fields have been obtained from satellite observations (such as GHRSST data), the other quantities were derived from ECMWF.

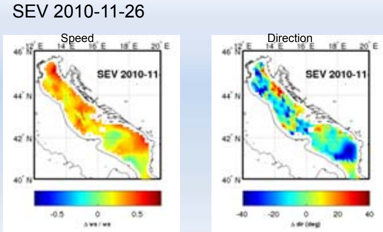
EO data wind tuning

Normalised bias $\Delta w/w_{scat}$ between ASCAT and ECMWF related to SEV 2010-11-26 for the Mediterranean Sea.



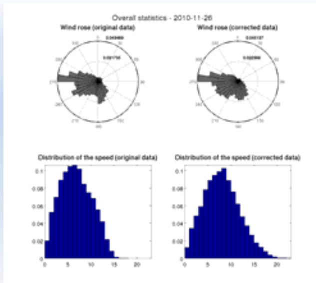
EO data wind tuning

SEV 2010-11-26



EO data
wind tuning

Statistics of the **tuned** data shows a longer distribution's right tail, meaning higher speeds in the extreme events.



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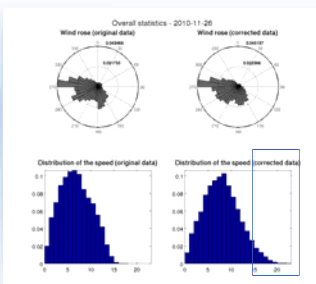


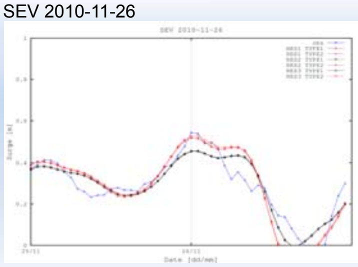
EO data
wind tuning

- TYPE1 = Original wind fields;
- TYPE2 = Tuned wind fields.

- RES1 = Full Resolution (1/8 degree);
- RES2 = Middle resolution (1/4 degree);
- RES3 = Low resolution (1/2 degree).

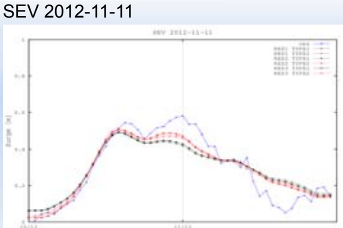
EO data
wind tuning

SEV 2010-11-26



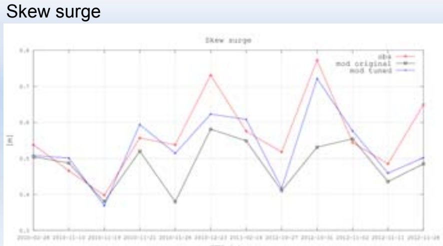
EO data: scatterometer

SEV 2012-11-11



EO data
wind tuning

Skew surge



EO data wind tuning

Statistics

EO data wind tuning

Statistics

	RMSE [m]	Correlation	Peak error [m]
		Original data	
Full res.	0.072	0.908	-0.102
½ res.	0.072	0.906	-0.102
¼ res.	0.073	0.904	-0.104
		Tuned data	
Full res.	0.066	0.918	-0.062
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EO data wind tuning

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EO data: scatterometer important remarks

What is the best temporal window to collect scatterometer data to tune the forecast wind fields?

- If it is too large it could not well represent that storm event;

- Scatterometer data should cover a wide part of the computational domain.

EO data wind tuning

Changes in spatial resolution do not affect too much the performances.

That is because storm surges are mesoscale phenomena and the correctness of the average wind speed and direction are more important than the resolution of local features.

But

All the configurations tested come from the same atmospheric model. Models with lower resolutions give lower average wind (e.g., previous ECMWF model versions).

Statistics are very similar with tuned wind, but the reproduction of the maximum peaks improves.

Part II EO data: altimeter

Altimeter data provide spatial information on the sea level.

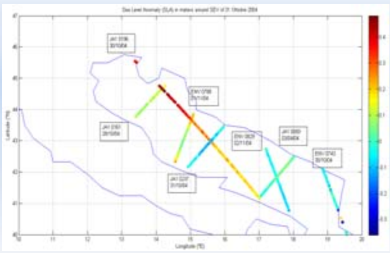
These data can be *assimilated* to improve the *analysis* state of the model and, consequently, the forecast.

STEPS:

- Find all the tracks in the computational domain and in the *assimilation window*;
- Process them in order to have quantities that can be assimilated (i.e., residual water level);
- Use them with a data assimilation technique.

EO data: altimeter find tracks

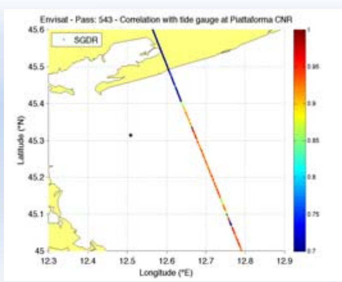
Example of altimeter tracks – SLA - SEV October 31, 2004



EO data: altimeter TWLE

Total Water Level Envelope is computed from the SSH corrected for ionospheric delay, wet/dry tropospheric delays, sea state bias, loading tides and solid earth tides.

Oceanic tides and the local response to atmospheric forcing are left.



EO data: altimeter Tide

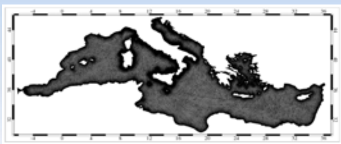
The storm surge model computes the response to atmospheric forcing. The astronomical tide must be subtracted from the TWLE.

How to find the tidal correction?

- Use the tidal correction provided with the data (from a model);
- Provide a new correction using a high resolution tidal model;
- Use a storm surge model with the tidal forcing included.

EO data: altimeter
Tide

- Run a tidal model for about 1 year;
- Find the coefficients from a harmonic analysis of the sea level in each node;
- Find the tide along the altimeter's tracks with an interpolation of the values in the nearest nodes.



EO data: altimeter

When is useful to assimilate altimeter data?

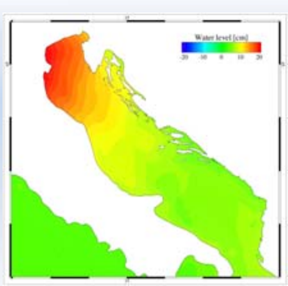
The initial state can be more or less important, depending on what processes the model must reproduce (complete calm, strong circulation, seiches, ...).

Find the spin-up time of the system to understand if the initial state is important or not.

EO data: altimeter
Seiche reproduction

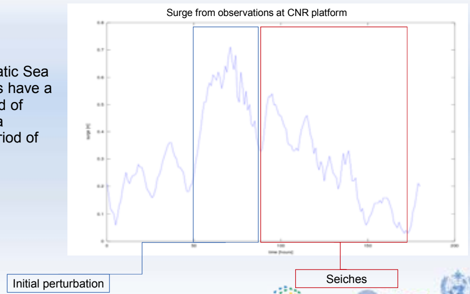
Seiches are important in the Adriatic Sea.

Seiches are free oscillations, happening in enclosed or semi-enclosed basins, following an initial perturbation of the sea level (i.e., a storm surge event).



EO data: altimeter
Seiche reproduction

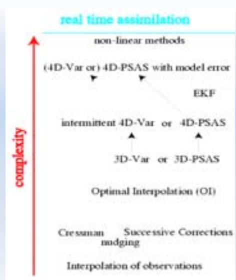
In the Adriatic Sea the seiches have a main period of ~22h and a second period of ~11h.



EO data: altimeter
Assimilation schemes

PURPOSE: to improve the accuracy of the initial state, using observations to *minimise* the errors.

The analysis state minimises a *cost function* where different sources of errors are considered.



From *Bouttier, F., et al. (1999)*

EO data
assimilation

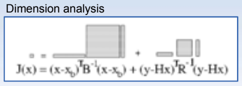
4D-VAR cost function

Find an initial perturbation δx_0, which minimises:

$$J(\delta x(t_0),\dots,c_i,\dots)=\frac{1}{2}\delta x^T B^{-1}\delta x \;+\; \frac{1}{2}\sum_{i=0}^{n}\left(H_i\delta x(t_i)-d_i\right)^T R^{-1}\left(H_i\delta x(t_i)-d_i\right) \;+\; \frac{1}{2}\sum_{i=1}^{n}c_i^T Q_i^{-1}c_i$$

Background errors — Observation errors — Model errors

Dimension analysis



See *Courtier, P., (1997)*

EO data assimilation

4D-PSAS is a “dual formulation” of 4D-VAR. The minimisation is made in the observation space.

4D-Psas cost function and gradient:

$$F(u)=\frac{1}{2}u^T\left(I+\sqrt{R^{-1}}GDG^T\sqrt{R^{-1}}^T\right)u-u^T\sqrt{R^{-1}}d$$

$$\nabla_u F=\left(I+\sqrt{R^{-1}}GDG^T\sqrt{R^{-1}}^T\right)u-\sqrt{R^{-1}}d$$

with:

$$d=y^0-Hx^b$$

$$\delta x=BH^T\sqrt{R}^{-1}u$$

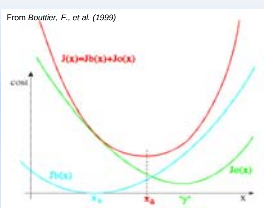
$$G=\left(\ldots,H_iM_{(t_i,t_0)},\ldots\right)$$

$$D=B\oplus\sum_i Q_i$$

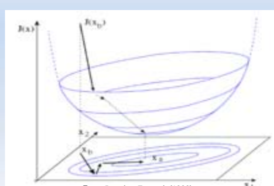
See *Courtier, P., (1997)*

EO data assimilation

From *Bouttier, F., et al. (1999)*



Cost function and minimisation algorithm



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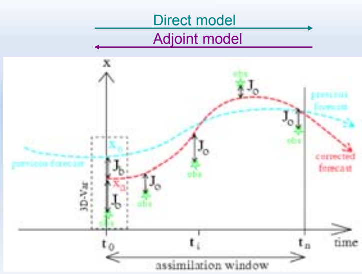
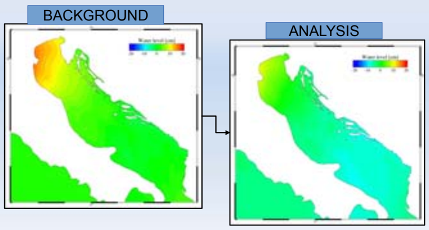
EO data assimilation



From *Bouttier, F., et al. (1999)*

EO data
Assimilation of tide gauge data

Assimilation of residual levels from tide gauges in the Adriatic Sea



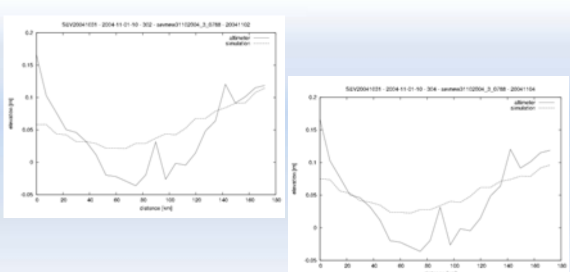
EO data
Assimilation of tide gauge data

Tide gauges can provide a good observational description near the coasts.

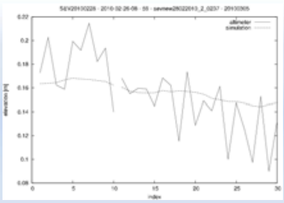
But in the open sea and near some coasts they are not present or can be not available

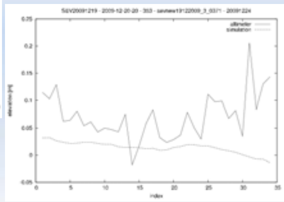
Altimeter data can supply to this lack

EO data
altimeter vs model



EO data: altimeter vs model





High frequency signals not reproduced by the model.
Altimeter data must be further post-processed

Concluding remarks

- What are the main sources of the forecast errors in the specific case? Is the wind bad estimated? Is the initial state important?
- What EO data are available operationally in the study area?
- Tuning the wind with scatterometer data improves the forecasts in all the storm surge events considered;
- Initial state can be improved with data assimilation;
- Altimeter data can provide informations where other observations are not available;
- Altimeter data must be carefully post-processed before being assimilated.