A SEMI-EMPIRICAL APPROACH FOR EXTREME SEA-LEVEL EARLY WARNING FORECASTS ALONG THE ITALIAN COASTS

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1 Introduction

Sea level variability is characterized by multiple interacting factors that act over wide range of temporal and spatial scales. Sea-level changes at decadal and interannual time scales are due to density and water-mass distribution variations in the ocean, driven by wind, atmospheric pressure and heat and water fluxes.

Atmospheric forcings produce, through mechanical stress, a displacement of the water mass involving sea-level variations due to barotropic displacement of the water column. Variations of temperature and salinity due to heat and water fluxes tend to modify the density structure of the water column (the steric effect), which in turn changes the height of the water column (mass conservation).

Sea-level changes in the global ocean are mainly driven by net water fluxes (precipitation, evaporation, river run-off and ice melting) which represents the sea-level variability component due to mass variations, and by buoyancy fluxes, which account for the steric component.

At the local level the lateral mass fluxes from the open sea areas and from the river deltas or estuaries also contribute to the mass budget and to the changes of mean sea level of the relevant coastal region (*Pinardi et al.*, 2013). In addition to the lateral mass fluxes just described, higher frequency motion, such as tides and wind waves, contribute to the increase of sea level and generate extreme sea level changes. Such extreme sea level events generate coastal flooding and there is need to have early warning systems to prevent human and property losses. Coastal flooding is in fact a major source of natural and man-induced hazards for the coastal areas of the world ocean (*Nichols*, 2004; *Nicholls and Cazenave*, 2010).

Early warning is defined by the International Strategy for Disaster Reduction as *'the provision of timely and effective information, that allows individuals exposed to hazard to take action to avoid or reduce their risk and prepare for effective response'* (*Grasso and Singh*, 2011). An Early Warning (EW) system results from the integration of four main elements: i) monitoring of relevant state variables, ii) hazard forecast; ; iii) information dissemination and iv) preparedness for response.

In this paper we focus the attention on the monitoring and forecast activities. The objective of this work is to design a sea water level EW system for target coastal areas along the
Italian coasts, using a semi-empirical model capable to use the numerical models data as forecasting components and observational data as calibration components.

The paper is organized as follow. In Section 2 a description of the observational data-set used is given. Section 3 describes the numerical models adopted to develop the sea water level (SWL) prediction system. Forecast calibration done using the observational data sets is described in Section 4. Section 5 shows the forecast skill of the SWL system obtained. All the results are summarized in Section 6.

2 Observations

In this work the in-situ data of Italian tide-gauge and wave-gauge networks, managed by the Istituto Nazionale per la Protezione e la Ricerca Ambientale (ISPRA), are used as reference and to calibrate forecasts. Tide-gauge network is composed of 26 stations covering the entire italian peninslula (Figure 1; red dots). On the other hand wave-gauge network counts 16 stations, whose positions are dispalyed in Figure 1 (green dots). Both observational networks provide operationally high temporal frequency meteoroligical and oceanographic data. At this stage of the SWL prediction system development, observational data are considered as 3-hourly mean, as will be described in detail in Section 3.

3 Sea Water Level forecasting system

Following the modelling system proposed by the CI-Flow Project (*Van Cooten et al.*, 2011), which developed a system that couples multiple atmosheric, hydrologic and hydrodynamic models to produce ensemble forecast of total water level, here we propose a method to obtain sea water level forecast in specific target areas (Figure 1), postprocessing different models outputs.

SWL can be expressed as :

$$(1) \quad \eta_{TOT} = \eta_{mass} \ + \ a_1\eta_{IB} \ + \ a_2\eta_{ST} + \ a_3\eta_{AT} + \ a_4\eta_{WA}$$

where η_{TOT} is the sea water level expressed as the resultant of the sea-level variations mass component (η_{mass}) due to wind driven water mass redistributions, water flux and lateral transport; the steric component (η_{ST}) due to variations of density of the water column; the atmospheric pressure effect on the sea-surface (η_{IB}) defined as inverse barometer effect; the sea-level variations due to astronomical tdes (η_{AT}); the sea-surface superelevation due to wave breaking η_{WA} defined as wave set-up.

The parameters a1, a2, a3, a4 are associated at each sea-level variation component, that has to be calibrated according to the part of physical signal and the geographical area considered.

3.1 *Hydrodinamic Component* (η_M)

In order to account the for the sea-level variations mass component (η_{mass}), the Mediterranean Forecasting System (MFS) outputs have beeen considered. The ocean general circulation model (OGCM) MFS has an horizontal resolution of 1/16 and 72 vertical levels (*Oddo et al.*, 2009); the model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using ECMWF data.

Since the model is forced by the wind and adopts incompressibility and Boussinesq approximations, we can assume that the sea-surface model output account for the SWL signal component η_{mass} and Eq. 1 can be written as :

$$(2) \quad \eta_{TOT} = \eta_M \ + \ a_1\eta_{IB} \ + \ a_2\eta_{ST} + \ a_3\eta_{AT} + \ a_4\eta_{WA}$$

where η_M is the sea-surface height model output, considered as hourly mean over the entire model domain and interpolated over the desired coordinates, that in this phase of the work are represented by the ISPRA stations positions (Fig. 1).

3.2 *Atmospheric Component* (η_{IB})

MFS model, up to now, do not consider the atmospheric pressure as vertical boundary considition, thus in order to consider the sea-level variations associated to the atmospheric pressure, the inverse barometer (IB) effect has to be added to the model outputs. Following the formulation of (*Dorandeu and Le Traon*, 1999) the IB effect can be expressed as the:

$$(3) \qquad \eta_{IB} = -\frac{1}{\rho_0 g} \ (Pa - P_{ref})$$

where h_{IB} is the sea-level anomaly due to an atmospheric pressure variation (Pa) with respect to a reference pressure value (P_{ref}).

The *atmospheric* component is computed starting from the data provided by the European Centre for Medium Range Weather Forecasts (ECMWF) (*Pinardi et al.*, 2003; *Pettenuzzo et al.*, 2010). ECMWF Forecast data are available every day from d to $d+10$, as 3-h forecast up to 72 hours and as 6-h forecast during the reaming period, with an horizontal resolution of 0.25 in the Mediterrannean basin.

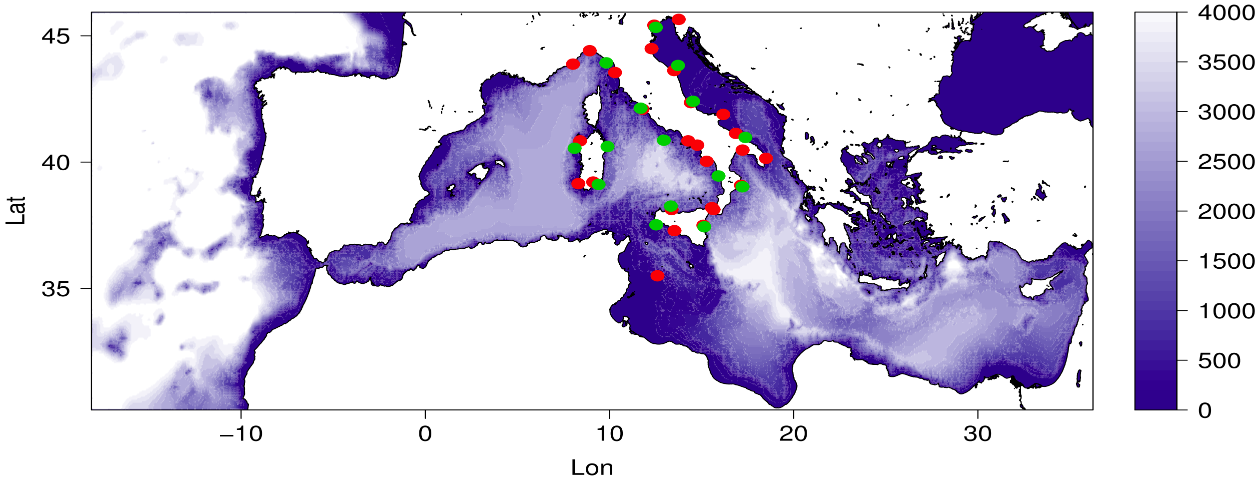

FIGURE 1. Ocean General Circulation MFS spatial domain and bathymetry. Circles show the tide-gauge (red) and wave-gauge (green) positions of ISPRA observational network.

3.3 *Steric Component* (η_{ST})

MFS model assumptions and approximations expressed Sub-section 3.1, involve on the other hand that the model do not consider volume variations of the water column. This aspect means that the steric component has to be added to the sea-surface height output of the OGCM models. In order to consider the entire sea-level signal, the steric effect has therefore to be superimposed on the data following *Mellor and Ezer* (1995)

$$(4) \quad \eta_{ST} = -\frac{1}{A} \int\int_A \left(\int_{-H}^{\eta} \frac{\rho - \rho_0}{\rho_0} dz \right) da$$

where A is the Mediterranean basin area, ρ is the ocean density (T, S, P) and ρ_0 is the reference density. In *Mellor and Ezer* (1995) the steric effect is consider for the basin scale as an only time dipendent variable. In our case, we want to obtain a SWL forecasting system in specific target area along the coast, thus the steric component is superimposed to the model data once tuned with the climatological data retrieved from the tide-gauge stations available.

3.4 *Tidal Component* (η_{AT})

The tidal elevations is obtained from the OTPS tidal model (Oregon State University Tidal Prediction Software: http://volkov.oce.orst.edu/tides/; *Egbert and Erofeeva*, 2002). The OTPS model provide for a given spatial domain the free-surface variations due to the astronomical tides, cosidering 8 tidal components: M2, S2, N2, K2, K1, O1, P1, K1.

As described in *Egbert et al.* (1994), tidal elevation is given as complex amplitude so that total tide as resultant of each of frequency w_l is given by :

$$(5) \quad h(t, x) = Re\left[\sum_{l=1}^{L} h_l(x) \; e^{iw_l(t-t_0)+V0_l(t_0)} \right]$$

where $h(t, x)$ is η_{AT} of Eq. 1 at the time t in the position x given by the constituent $h_l(x)$ and $V0_l(t_0)$ is the astronomical argument for the constituent at time $t0$ for costituent l .

3.5 *Wave Component* (η_{WA})

Waves can induce sea-level variations through a process called wave set-up, defined as the sea-surface superelevation due to the transfer of momentum from the wave to the water column at the breaking. Wave set-up process involve as well a setdown phase, resulting in a wave-induced decreasing of sea-level in the breaking zone. In the sufzone the sea-level tend to increase between the breaking point and the shoreline (setup). The resultant of the wave setdown and setup is commonly defined as wave set-up.

MFS model is coupled with the spectral wave model WaveWatchIII (WW3; *Tolman*, 2009) using a two ways coupling: surface currents and SST computed by the ocean general circulation model are transferred to the wave model, while the neutral drag coefficient computed by the wave model is passed to the ocean model with 1-h frequency. The WW3 model forecast outputs, available as hourly data for the entire Mediterranean basin, can be used to compute as postprocessing the wave set-up, starting from the significant wave height and the wave mean period fields.

At this stage of development, the system do not considered wave setup η_{WA} signal, whose implementation within the SWL forecasting system needs further investigations since, as noticed by *Ferrarin et al.*, 2012, the effect of this component is not that relevant if the models horizontal resolution is in the order of kilometers, since wave set-up is a processes that occurs in the surf zones that generally in the Mediterranean Sea has an extensions of few hundred meters also during storms.

3.6 *Reference system*

The sea-surface height model output is referred to the model *zero* level, defined by the topography adopted by the model. This aspect involve that model and observations have a different reference systems, thus we consider the signals as anomalies obtained subtracting the mean value from each data-set (*Guarnieri et al.*, 2012). Finally the mean values obtained from the observations are added to the model outputs, in order to refer the two data-set to the same reference system.

3.7 *Parameters definition*

The parameters a_1, a_2, a_3 and a_4 (Eq. 1) are estimated through multiple linear regressions performed using the observation data-set in order to tune each SWL signal component considered, accounting for the mean values and residuals retrieved from obsevations.

3.8 *SWL forecasting system output*

SWL forecasting system described above is operational at the Centro Euro Mediterraneo sui Cambiamenti Cimatici, providing monitoring and forecasting informations for 26 target locations (Figure 1, red circles). Data are available over a nine days time window, considering 7 days of observational data and 2 days of forecast data, as 3-hours mean. Every day the time window considered is shifted 24 hours ahead. Up to now only a single run per day is performed, while in the near future the number of run per day will increase significantly, in order to update the forecasts data several times during the 24 hours.

4 Standard and combined forecast

During each SWL forecasting system run, three ditterent types of forecast are obtained for each location considered. At first a SWL forecast, hereafter called *standard forecast*, is obtained as described in Section 3. Once the standard forecast is available, *calibrated forecast* and *calibrated ensemble forecast* are obtained using a bayesian method for combining forecasts (X) with observations (θ) (*Coelho et al.*, 2004; *Stephenson et al.*, 2005). The method is based on three main steps: (i) choice of the prior distribution, (ii) modeling of the likelihood function, and (iii) determination of the posterior distribution.

The posterior distribution $p(\theta_t|X_t = x)$ is found from the prior $p(\theta_t)$ making use of the Bayes theorem:

$$\text{(6)} \qquad \overbrace{p(\theta_t|X_t = x)}^{\text{posterior}} = \frac{\overbrace{p(X_t = x|\theta_t)}^{\text{likelihood}}\,\overbrace{p(\theta_t)}^{\text{prior}}}{p(X_t = x)}$$

where the prior distribution $p(\theta_t)$ is represented by probability density function of the observations at the time t, and x is a particular value of forecast at the time t. In other words the prior represent our knowledge of the phenomenon in the past, that can be updated once a forecast $(X = x)$ is known in the future, in order to obtain the conditional posterior distribution $p(\theta|X = x)$. Figure 2 schematize the method described.

Using this method the calibrated forecast is obtained combinig the standard forecast with the observations. On the other hand, the calibrated ensemble forecast is obtained combining the observations with the ensemble mean forecast. Three ensemble members are considered, each of them stand for a different physical representation of the SWL signal:

– Standard forecast (η_{TOT}).

– Forecast obtained considering mass (η_M), steric (η_{ST}) and tidal (η_{AT}) components

– Forecast obtained considering tidal (η_{AT}) and atmospheric components (η_{IB}).

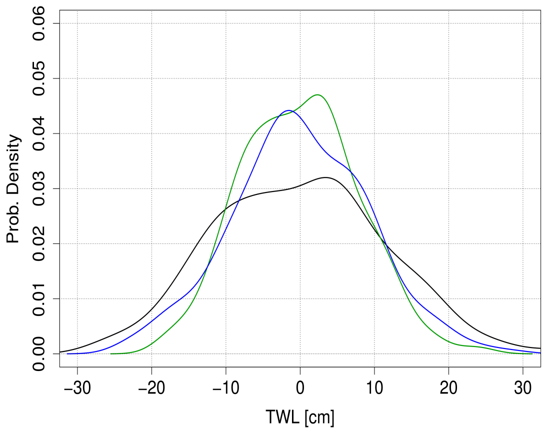

FIGURE 2. Prior distribution (black line), likelihood (green line) and posterior distribution (blue line).

5 SKILL EVALUATION

Sea water level system (SWLs) skill is evaluated comparing the first and the second day of forecast with the ISPRA tide-gauge network data in terms of anomaly correlation coefficient (C), root means square error (RMS) and normalized root mean square error (RMSsd), for the first and the second day of forecast. In Table 1 are presented the results for the standard, calibrated and calibrated ensemble forecast, where rows indicate the first and the second day of forecast, considering the mean of the target locations included in the system over a reference period of 1 month. Considering the standard forecast, the skill for the fisrt day of forecast in term of anomaly correlation coefficient is $\sim$ 0.5 with an RMS of $\sim$ 5.5 *cm*, that increase up to $\sim$ 7.5 *cm* considering the second day of forecast. It is possible to notice how the system skill tend to increase, both for the first and second day of forecast, considering the calibrated and calibrated ensemble forecast where the anomaly correlation coefficient grows up to 0.86 with a RMS of 3.21 *cm*.

In Figure 3 is presented a synthetic view of the SWL forecasting system skill. The taylor diagram shows the statistisc of the simulated SWL with respect to the observations considering the standard (black), calibrated (blue) and calibtrated ensemble (red) forecasts, where cirlces and diamonds refer to the first and the second day of forecast respectively.

6 SUMMARY AND CONCLUSIONS

A semi-emphirical model for SWL forecasting has been develop for the Italian coasts, using numerical models and in-situ observations as forecasting and calibration component respectively. In particular each component of the SWL signal is retrieved from a different numerical model and calibrated with the closest observations: i) mass component is given by the OGCM MFS (Sub-section 3.1) ; ii) the steric component is obtained as function of temperature and salinity fields of the OGCM MFS; (Sub-section 3.3); iii) the atmospheric component is considered starting from the ECMWF atmospherical model oputput (Sub-section 3.2); iv) the tidal component from the OTPS model 3.4). At this stage of development, the system do not considered the SWL signal due to wave-setup η_{WA}, as described in Sub-section 3.5.

The forecasting system developed show skill with respect to the observational data of the Italian tide-gauge network. A bayesian approach has been adopted in order to combine and calibrate forecasts with observations and to obtain different forecast realizations. In this way, starting from the standard forecast obtained as described in Section 3, also a calibrated and a calibated ensemble forecast are availbale at each system run. The prediction obtained considering three ensemble members (Section 4) show the higher skill in terms of anomaly correlation coefficient and RMS up to the order of $\sim$ 0.85 and 3.2 *cm* respectively during the first day of forecast, and $\sim$ 0.8 and 3.8 *cm* during the second day of forecast.

In conclusion the system developed can represent a monitoring and forecasting tool to be included in an Early Warning system for sea-level extreme events along the Italian coasts.

	Standard			Calibrated			Calibrated Ensemble		
	C	RMS	RMS_sd	C	RMS	RMS_sd	C	RMS	RMS_sd
1	0.51	5.52	0.95	0.55	4.85	0.83	0.86	3.21	0.55
2	0.32	7.52	1.29	0.35	5.53	0.95	0.79	3.80	0.65

TABLE 1. Standard, Calibarted and Calibrated Ensemble forecasts skills. Rows indicate the day of forecast; columns indicate the anomaly correlation coefficient (C), the root mean square error (RMS) and the normalized root mean square error (RMSsd) respectively.

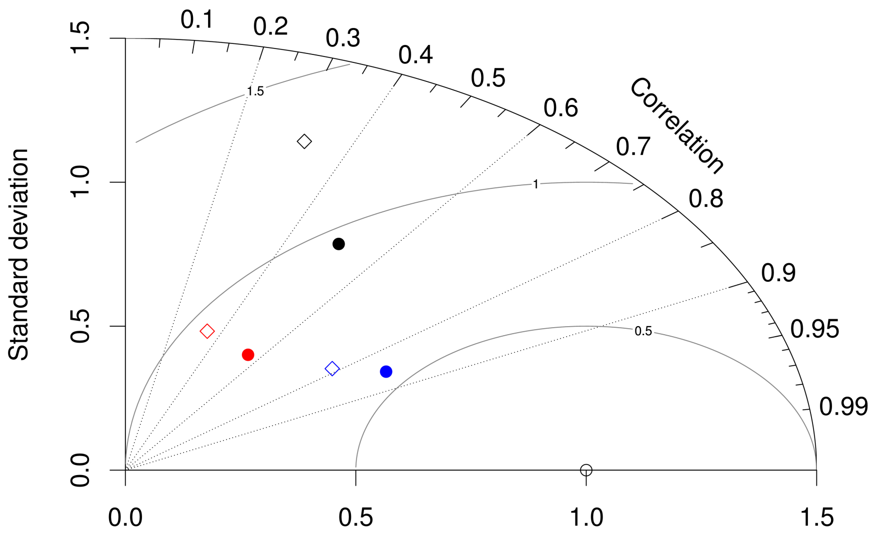

FIGURE 3. Taylor diagram showing the comparison with observation of forecasted SWL signal, considerig standard (black), calibrated (red) and calibrated ensemble (blue) forecast. Circles refer to the first day of forecast; diamonds refer to the second day of forecast.

The future work will be centered on the implementation of the η_{WA} component in the SWL forecasting system and on the reasearch and analysis of new observational data-set, both in-siu and remote sensing, in order to test the calibration component with larger data-sets and to attemp to extend the spatial domain of the SWL system to the entire Mediterranean basin.

7 Aknowledgements

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