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PROPAGATION OF UNCERTAINTY ACROSS THE MODELING CHAIN FOR EARLYWARNING OF COASTAL STORMS IN THE EMILIA-ROMAGNA REGION

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Abstract

The present study analyses the propagation of the uncertainties through an integrated numerical modeling chain that is composed by the meteorological model COSMO, the wave/oceanographic models (SWAN and ROMS) and the coastal model XBeach. The ensemble approach was used to investigate how the uncertainty propagates from off-shore meteorological forecasts to on-shore vulnerability to coastal flood. The research focused on a storm event occurred in the winter 2015along the coasts of the Emilia-Romagna region located in the North-East of Italy. The outputs of the models were compared with the measured data collected during the storm. The research confirms that the inaccuracy of the meteorological forecasts propagates up to the coastal model, affecting the forecasts of the morphological variations. The ensemble approach seems to be the most promising methodology to quantify the overall uncertainty.

Key words: ensemble prediction, probability forecasting, early warning, numerical modelling, numerical models

1. Introduction

A significant part of the coasts of the Emilia-Romagna region, in the North-East of Italy, is affected by coastal hazards due to intense storm events of the Adriatic Sea. The correspondence of high wave energetic conditions and high water levels, can cause significant damages and serious erosive phenomena on the littoral and their behind areas (Gracia et al., 2014). The prediction of these hazards can provide valuable information for civil protection and coastal management issues(Plomaritis,2012).

Many countries in the world developed early warning systems for coastal flooding (Doong et al., 2012, Gracia et al., 2014, Bogaard et al., 2016, Valchev et al., 2014). The modelling framework consists of an integration of meteorological and wave/ oceanographic models which are extended with morpho-dynamic response (Baart, 2009) of the near-shore/surf zone models.

The interactions between atmospheric, oceanic and coastal processes are poorly understood, resulting in large uncertainties in the predictions of coastal flooding, in particular, under extreme conditions (Baart,2011; Zou,2009).

The Emilia-Romagna Early Warning System (EWS) is a state-of-the-art coastal forecasting system, composed by a series of numerical models, to provide a forecast up to 72 hoursahead of the sea level along the entire coastal region (Harley et al., 2016). The EWS consists of an integrated numerical modeling chain that is composed by the meteorological model COSMO(www.cosmo-model.org), the wave/oceanographic models, SWAN (Ris et al., 1994), and ROMS (Chiggiato and Oddo,2006), and the coastal model XBeach (Roelvink et al., 2009).

Since a deterministic forecast cannot give any indication on the reliability of the model forecasts, the ensemble methodology is more and more frequently adopted to have an estimate of the model error. Indeed, the use of the probabilistic approach via the ensemble forecasting has now become commonplace to tackle the chaotic behavior of the atmosphere and to support forecasters in the management of events with little deterministic predictability (Montani et al., 2011) providing different forecasted scenario and an estimate of the associated forecast accuracy.

This paper presents a sensitivity analysis of this integrated numerical modellingin order to define how the uncertainties propagate through the cascade models and to improve the understanding of the coupling between atmosphere, ocean and coast in relation to their importance for coastal flooding. The objective of the research was assessed through the use of the ensemble approach in order to improve our understanding of the reliability of results (Zou and Reeve, 2009; Dance and Zou, 2010).

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The ensemble analysis of the entire modeling chain was preceded by a sensitivity analysis of the coastal model XBeach which is the ending model of the EWS.
The study uses a storm event occurred on the Emilia-Romagna coasts in November 2015 as test case to illustrate the proposed approach. Topographic and bathymetric reliefs of 10 cross-shore beach profiles were carried out after and before the storm event, to give an evaluation of the models performance.

The paper is organized as follows. Section 2 describes the numerical modeling chain and the meteorological operational ensemble system. Section 3 details the study approach used in this paper to study the uncertainties propagation, while the features of the storm event, used as test case, are presented in Section 4. The results of the sensitivity analysis of the coastal model and the outputs of the ensemble approach are summarized in Section 5.Conclusions and plans for the future work are given in Section 6.

2. Description of the modeling chain

The integrated modeling system operational at Arpae SIMC Emilia-Romagna consists of a wave modeling forecasting chain, named Meditare (Valentini et. al., 2007) based on the SWAN model (Ris et al., 1994), and an oceanographic model ROMS, implemented on the Adriatic Sea, named AdriaRoms (Chiggiato and Oddo,2006). Both models are driven by the weather forecast numerical model COSMO (www.cosmo-model.org),forced by the ECMWF model (www.ecmwf.int) with a 7 km resolution. The outputs from the coupled operational meteo-marine chain are used as input data for the coastal model XBeach (Roelvink et al, 2009) that was implemented as part of the FP7-MICORE project activities (www.micore.eu) and integrated in a coastal early warning system for the Emilia-Romagna Region (Harley et al., 2016). The operative chain (Figure 1) provides a forecast up to 72 hour ahead. A brief overview of each model is given in the following.

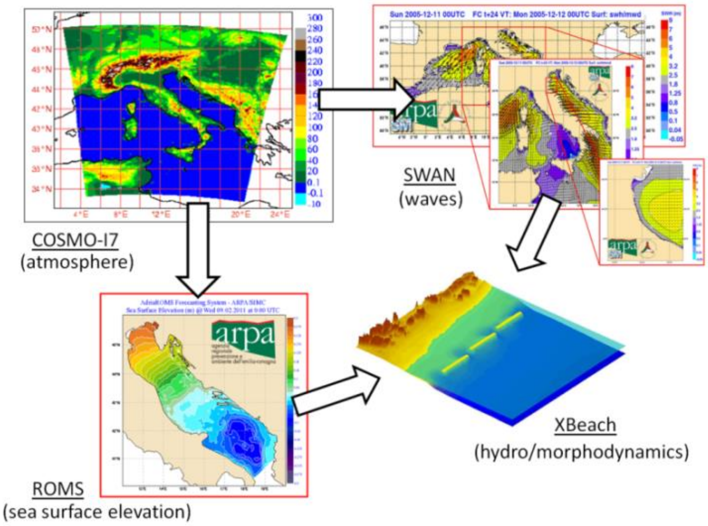

Figure 1. Operational numerical forecasting chain at Arpae SIMC Emilia-Romagna for the coastal Early Warning System.

The COSMO model is a state of the art non-hydrostatic numerical weather prediction model and it is developed by the Consortium for Small-Scale Modelling. Boundary conditions are provided by the European Center for Medium Range Weather Forecasts, ECMWF. Arpae-SIMC developed COnsortium for Small-Scale MOdelling Limited-area Ensemble Prediction System (COSMO-LEPS) on behalf of the COSMO consortium (Marsigli et al. 2001, Montani et al. 2011). It consists of 16 integrations of the non-hydrostatic mesoscale model COSMO, over the same area up to 5 days ahead.
AdriaROMS is the operational oceano-graphic model system for the Adriatic Sea running at Arpae-SIMC. It is based on the model ROMS (Regional Ocean Modeling System, Haidvogel et al., 2008) for the Adriatic Sea, in the Mediterranean. It is forced by astronomical tides derived from the OTIS database (Egbert and Erofeeva, 2002 TS3), by the oceanographic fields (salinity, temperature and currents) provided by the Mediterranean Ocean Forecast-ingsystem (MFS, Oddo et al., 2009) and by the fields of the atmospheric

model COSMO (namely 10 m wind, mean sea level pressure, 2 m temperature, 2 m relative humidity, cloud cover, precipitation rate and short-wave solar radiation).

SWAN is a non-stationary third-generation wave model, developed at Delft University of Technology, that computes random, short-crested wind-generated waves in coastal regions and inland waters. The model is forced with 10m wind output from the atmospheric model COSMO.

Finally, XBeach is a 2DH (depth averaged) model that solves coupled short wave energy, flow and infragravity wave propagation, sediment transport and bed level change. The model can simulate wave run-up and overtopping at structures, dunes and beaches (Stelling and Duinmeijer, 2003; Roelvink *et al.,* 2009).

3. Methodology

The methodology consists of two steps: a sensitivity analysis of the coastal model XBeach and a sensitivity analysis of the numerical modeling chain applied with the ensemble approach.

The analysis of the XBeach model focused on a sensitivity study to define the influence of the parameters variation on the model output sand to produce a proper model setup for the next ensemble analysis. An approach “one-at-the-time” was followed (Simmons et al., 2015). For each simulation, a single parameter was varied within their validity range while the other were kept constant at their default value. The effect of several parameters related to sediment transport and morphological changes was examined, while the default values (Roelvink et al., 2010) for each parameter was used to generate a reference simulation.

The model was applied along 2cross-shorebeach profile sand was forced by the data observed during a storm event occurred in winter 2015-2016 along the Emilia-Romagna coasts.

The outputs, including the foreshore eroded volumes, the shoreline retreat and the wave run-up, were compared each simulation with the corresponding reference outputs, through the Sensitivity Index, as follows:

$$\mathrm{SI}_{\mathrm{n}} = \frac{Value_n}{Value_{default}} \tag{1}$$

where n indicates the number of the simulation.

The model performance was also assessed by means of the *Brier Skill Score (BSS).* The correlation of the measured profiles (pre-storm x_b and post-storm x_p) and of the modeled profile (x_m) can be expressed as follows (2):

$$BSS_n = 1 - \left(\frac{\left\langle \left| x_m - x_p \right|^2 \right\rangle}{\left\langle \left| x_p - x_b \right|^2 \right\rangle} \right) \tag{2}$$

The BSS is commonly used as the statistical indicator of the performance of the numerical model especially for morphological changes (Bugajny et al., 2013). Specifically: BSS <0*bad*, 0< BSS <0.3 *poor*, 0.3< BSS <0.6 *reasonable/fair*, 0.6< BSS <0.8 *good* and 0.8< BSS <1 *excellent* (Van Rijn et al., 2003).

The measured and computed foreshore eroded volumes were compared with the measured eroded volumes to define their discrepancy. The best model skills are associated to the near zero values of this discrepancy.

The second step of the study consisted of the analysis of the uncertainties propagation through the integrated numerical modeling chain via the ensemble approach. The wave/oceanographic models, AdriaROMS and SWAN, was forced by the 16 ensemble scenarios of the COSMO-LEPS model (Marsigli et al., 2005). The outputs of these models, in particular wave and sea level time series, were used to drive the coastal model XBeach, providing 16 different sea state conditions to forcing the model. Figure 2shows the ensemble modelling framework used for the analysis.

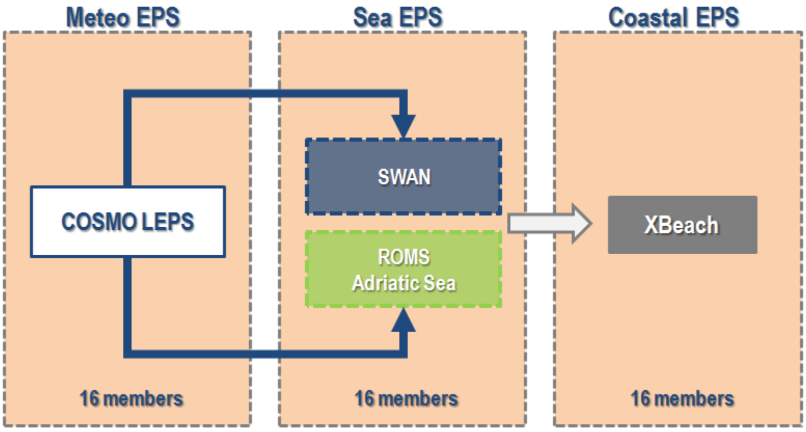

Figure 2. Integrated ensemble modelling framework for the analysis of the propagation of the uncertainties through the integrated modeling chain for the Early Warning System.

The ensemble analysis was finalized to have an indication of how the uncertainty propagates through the model cascade which constitutes the early warning system for the coastal flooding.

To achieve the goal of the research, several wave/oceanographic and morphological variables at different step of the numerical chain were analyzed, specifically: the wave height, the wave spectrum, the sea levels and the eroded volumes of the foreshore beach.

The ensemble statistics, mean and spread, were evaluated for the single variables in order to make a comparison with the corresponding measured data.

4. Description of the case study

The Emilia-Romagna region, which owns about 110 Km of coastal areas, is located in the North-East of Italy. This littoral, characterized by low and sandy beaches (Perini et al., 2011), overlooks the Northern Adriatic Sea, with an orientation North-West to South-East.

Many stretches are protected by hard defenses (groyns, detached breakwaters, sea-wall etc..) and systematically nourished to ensure inland protection and preserve recreational activities and tourism (Aguzzi et al., 2016).

Most intense storm events are mainly associated with Bora weather conditions, blowing along the north-east direction and with Scirocco winds that coincide with the main SE-NE axis of the Adriatic Sea (Martinelli*et al.*, 2010). These conditions cause several direct and indirect impacts on the coastal areas, increasing the coastal vulnerability to inundation of the hinterland areas.

The study area is a 1 km long coastal stretch close to the touristic resort of Cesenatico (Figure 3). This coastal stretch consists of an unprotected medium-fine sandy beach.

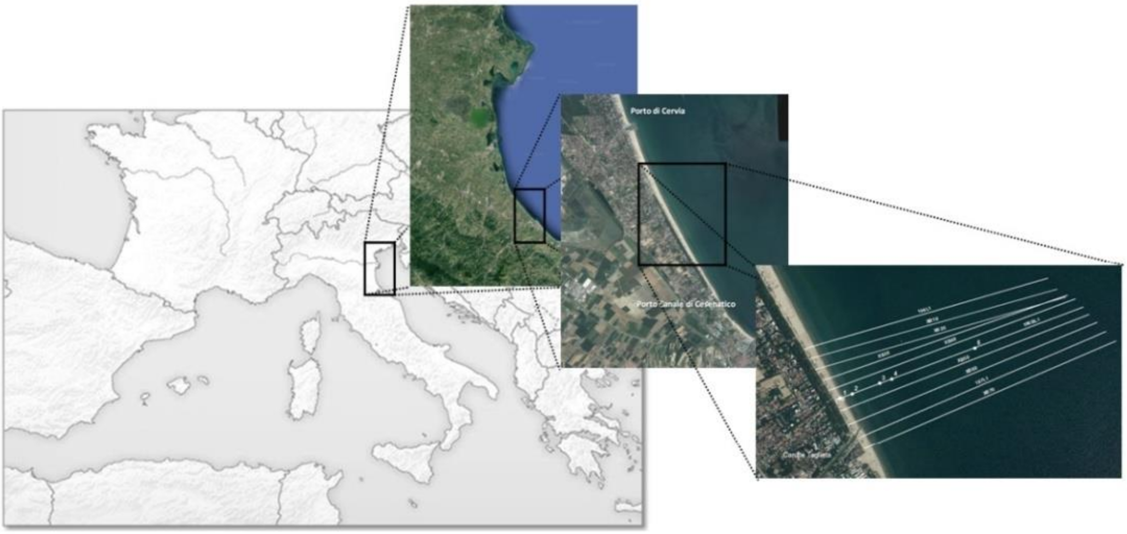

Figure 3. Map of the Cesenatico study site, Northern Italy

Topo-bathymetric and sedimentological surveys took place along 10 cross-shore transects (Fig.1), with spacing of about 100 m. The topographic and bathymetric reliefs covered both the emerged and the submerged beach, starting from the highest point of the beach up to the bathymetric of 8 m. The surveys were carried out after and before a storm event, occurred on the Emilia-Romagna littoral during the winter 2015. The wave data were retrieved by the wave buoy placed off-shore Cesenatico (https://www.arpae.it/sim/?mare/boa) and the sea level conditions were obtained by the tidal gauge located at Rimini (Figure 4).

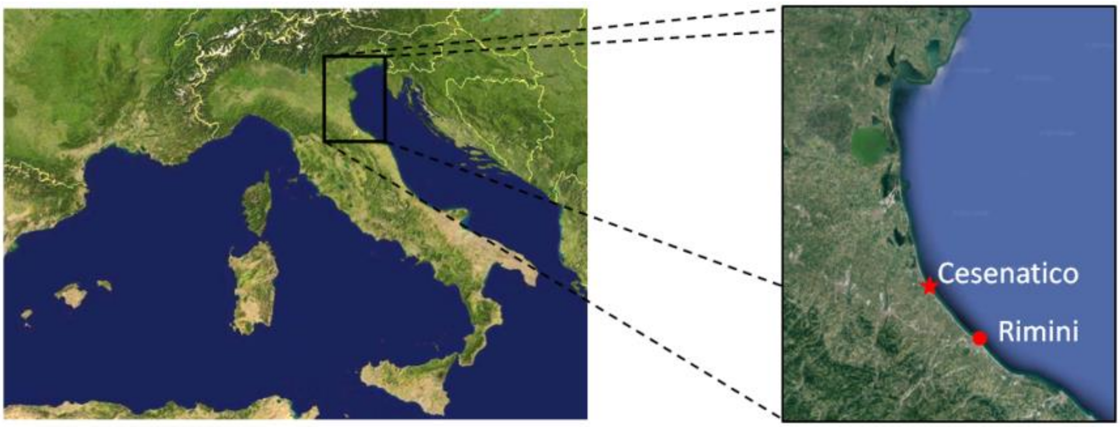

Figure 4. Location of the study site (Cesenatico, red star) in the Emilia-Romagna region located in the North of Italy and the tide-gauges of Rimini (red dot).

The features of the storm event are shown in Figure 5.The storm is a one-day event started in the late afternoon of the 21 November 2015. The significant wave height H_s of the event reached the value of 3.30 m on the 21 November 2015 at 23:00 UTC. The mean wind direction represents a characteristic Bora wind event.

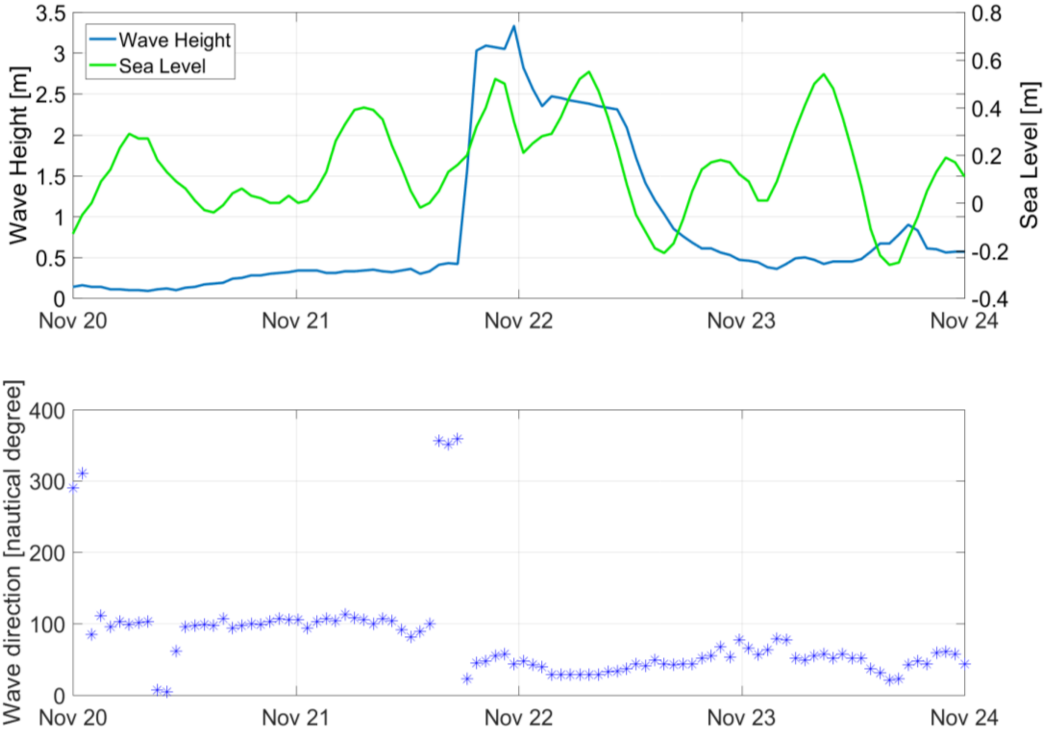

Figure 5. Features of the storm event. Upper panels: significant wave height by the Arpae wave buoy Nusicaa (blue line) and sea level by the Rimini tide gauge (green line). Bottom panels: main wave direction measured of the wave buoy Nausicaa

5. Results

5.1 XBeach Sensitivity Analysis

The sensitivity indices related to the single parameters were calculated for shoreline retreat, eroded volumes of the foreshore beach and runup (Figure 6) and highlighted the higher influence of the following parameters: gamma (breaker index in the wave breaking formulation), facua (calibration factor for both wave asymmetry and skewness), facAs (calibration factor for wave asymmetry), facSk (calibration factor for wave skewness), delta (Fraction of wave height to add to water depth), break (type of breaker formulation), fw (bed friction factor) and bedfric (friction coefficient of flow).

The values of the BSS calculated for each simulation show that only the variation of the parameters *facua* and *fw* allows to obtain a good prediction of the morphological changes. *Facua* is related to wave asymmetry and skewness; and it enhances the effect of predicted wave non-linearity, affecting also the estimated sediment transport rates. The *fw* parameters a user-defined bottom friction factor and it is used in the calculation of the wave energy dissipation. As an example, Figure 7 shows the measured and the forecasted foreshore eroded volumes with varying these relevant parameter (*facua* and *fw*).

The values of the facua parameter in the range 0.25-0.30 provide a maximum BSS equal to 0.62 (*reasonable/fair)* while a BSS of 0.86 (*excellent*) is reached for *fw* equal to 0.2.

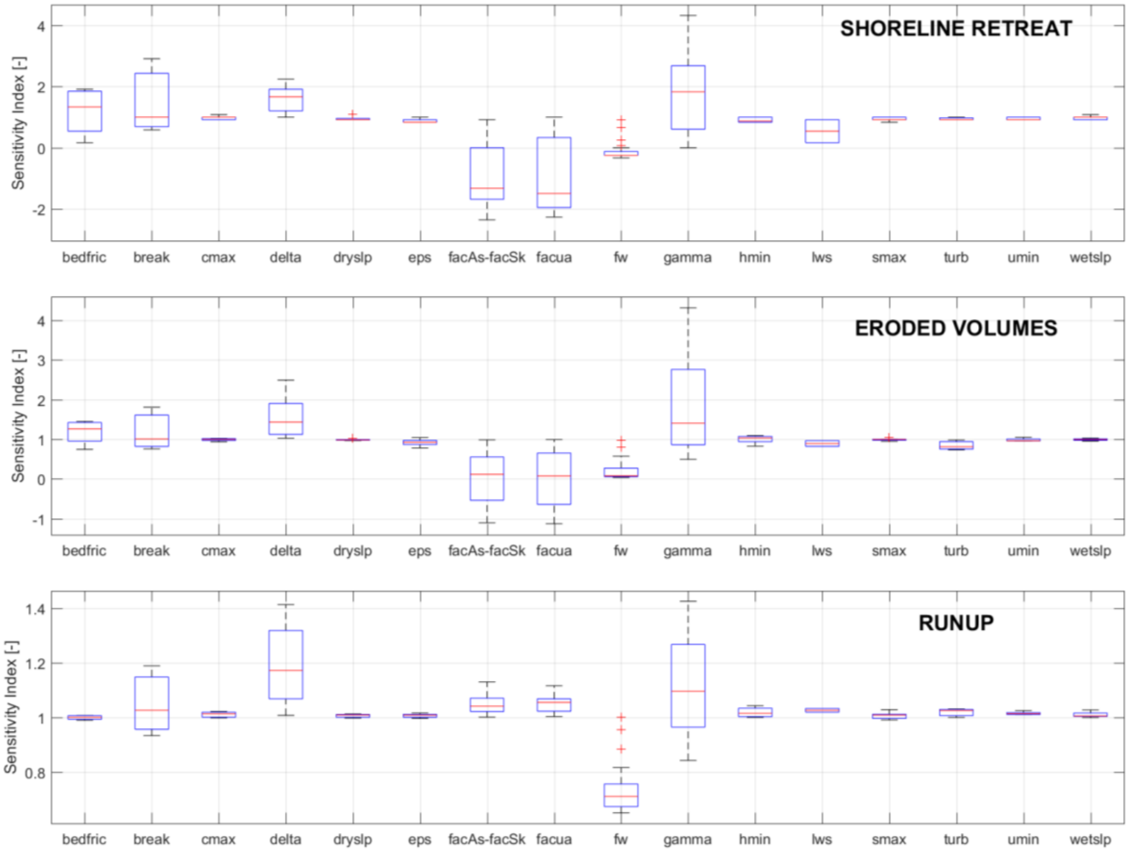

Figure 6. Sensitivity Indicesevaluatedfor the single model parameters, related to foreshore eroded volumes (upper panel), shoreline retreat (central panel) and runup (bottom panel).

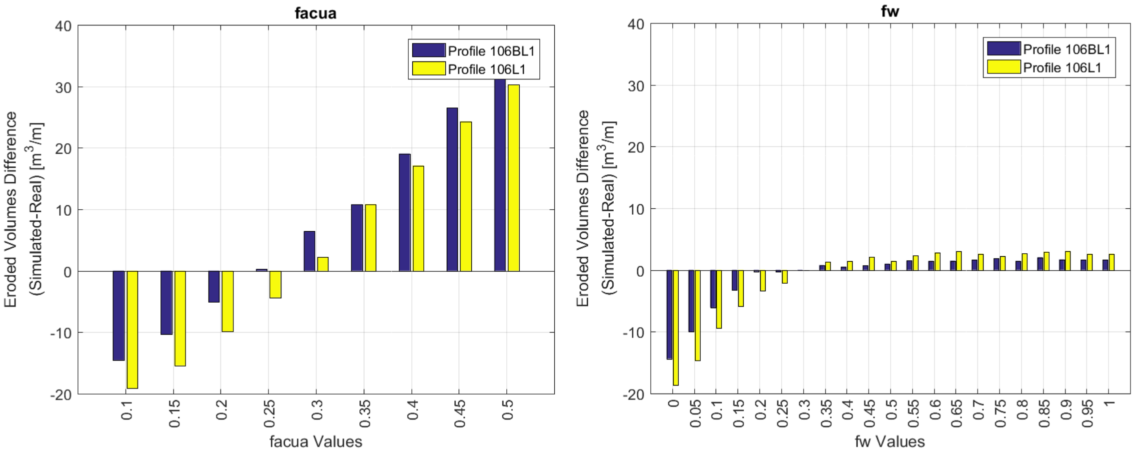

Figure 7. Difference between the simulated and measured foreshore eroded volumes for *facua* (left panel) and *fw* (right) parameters. The different colors represent two different cross-shore profiles

5.2 *Ensemble Analysis of the Numerical Chain*

The remarkable discrepancy between the measured wave heights by the Nausicaa buoy and the mean of the ensemble forecasted wave height, is presented in (Figure 8). Even if, the spread of the ensemble members increase in correspondence of the peak of the storm, it is not able to reproduce the measured wave height. The deviation of the ensemble members from the buoy data shows an underestimation of the event intensity. Probably, this may be associated with the difference between the real conditions (ECMWF operational mean sea level pressure analysis –black isolines) and the COSMO LEPS ensemble mean forecast (green isolines) visible in Figure 8.The different position of the minimum of the mean sea level pressure at 2015-22-22 00:00 leads to a variation of the wind and intensity direction. Even if the forecast at the Adriatic basin scale gives a good representation of the event, the model is not able to accurately reproduce the circulation associated to intense winds towards the coast at local scale.

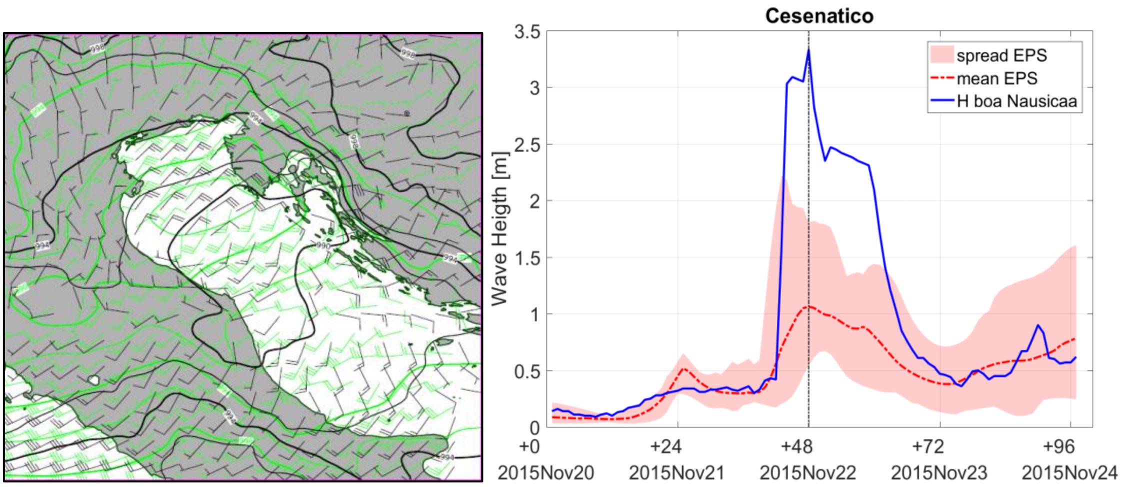

Figure 8. Left panel: Comparison of the ECMWF analysis (black) and the deterministic run of COSMO-LEPS (red) after +48 h forecasts. Right panel: Comparison of the wave heights measured by the Nausicaa buoy (blue line) and the ensemble forecasted wave heights. The ensemble mean (red dashed line) and the ensemble spread (shadow zone) are displayed.

The ensemble wave spectral density is shown to be substantially lower than the observed spectrum, see Table 1. The oceanographic model Adria-ROMS (Figure 9) is not able to capture the peak storm level as can be deduced by the high sea level forecast spread. However, the sea level trend is fairly reproduced.

Table 1. Power Spectral Density[m2/Hz] for the measured wave spectrum, collected by the Nausicaa buoy, and the ensemble forecasted spectra, in correspondence of the maximum wave height of the event. For the ensemble members statistical values (average, maximum and minimum) are presented.

	Frequency range [Hz]					
	0.05-0.15	*0.15-0.25*	*0.25-0.35*	*0.35-0.45*	*0.45-0.55*	*0.55-0.65*
Measured (Boa)	47.52	18.48	3.60	0.52	0.13	0.02
Ensemble Max	6,18	4,41	1,15	0,17	0,07	0,03
Ensemble Average	2,05	1,87	0,46	0,07	0,03	0,02
Ensemble Min	0,27	0,53	0,08	0,02	0,01	0,00

The ensemble simulations underestimate the erosion processes of the foreshore beach, see Figure 10.
For all the variables, the verification against the measured data clearly shows the good agreement between the higher spread of the forecasts and the lower predictability of the storm event, as visible for the wave heights intensity (Figure 8, right) and peak storm level (Figure 9).

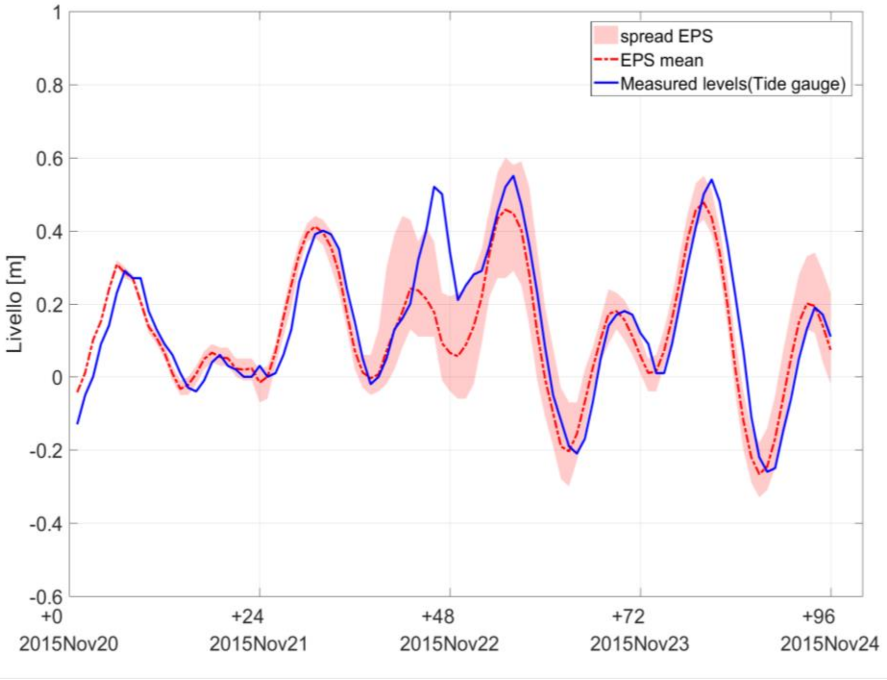

Figure 9. Sea level ensemble forecasts (green lines) and measured levels by tide-gauge of Rimini (blue line). The red line represents the ensemble mean.

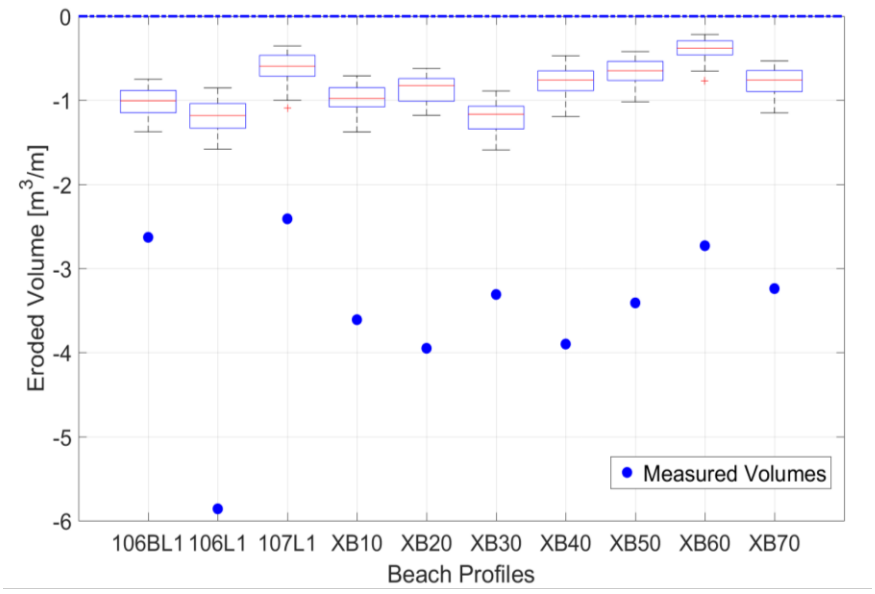

Figure 10. Morphological evolution. The measured eroded volumes are indicated by the blue dots while the box-plots represent the corresponding outputs of the ensemble members. The eroded volumes are evaluated for the foreshore beach.

6. Conclusions

This study presented a preliminary analysis of the propagation of the uncertainty through the numerical forecasting chain composed by the meteorological model COSMO, the wave/oceanographic models SWAN and ROMS, and the coastal model XBeach. This chain constitutes the Early Warning System for coastal flooding, for the Emilia-Romagna region (Italy).

The methodology was applied to a monitored storm event, occurred in winter 2015, to evaluate the coastal model sensitivity to different setting parameters and the propagation of the uncertainties from the meteorological up to the morphological component of the chain, using the ensemble approach. The errors predicted by the ensemble forecasting system were assessed through the comparison among the forecasted and the corresponding measured variables obtained by topo-bathymetric reliefs of the beach profiles.

The sensitivity analysis of X-beach, by varying the parameter related to the wave shape (*facua*) and the bottom friction factor (*fw*), confirmed the importance of the proper model calibration based on the local morphology.

Despite the uncertainties in each model variables, and the uncertainty propagation from meteorological to coastal models, the outputs of the ensemble modelling system are in agreement with the observed real sea state conditions. Indeed, there is a good correspondence between the forecast error and the ensemble spread.

The underestimation of the storm wave heights intensities, of the storm spectrum energy and of the peak sea level corresponds to a larger spread of the ensemble members with a good indication of a lowering of the intensity of the event predictability.

These results indicate the predominant role of the meteorological component in the overall error. The general wind underestimation in all the meteorological ensemble members dominates the subsequent evaluation of the morphological evolution with a systematic error which is not compensated by the ensemble spread of the eroded volumes.

These preliminary results show the importance of a better knowledge about the overall uncertainty associated with a coastal early warning system based on a cascade modelling system. The ensemble approach, already used in numerical weather prediction, is the most promising methodology to asses this uncertainty.

This work is still in progress. Other sources of uncertainty will be investigated trying to optimize the relationship between the coupled modeling chain error and the spread of the coastal model forecasts.

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