Probabilistic EWS for coastal risk implemented and tested on at least one location along the Emilia-Romagna coast

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INTRODUCTION

During the STREAM project, the setting up and operational implementation of a probabilistic approach based on the XBeach model for coastal risk has been performed. The system will use the outputs of sea level and wave parameters of the multi-model ensemble oceanographic forecasting system. Two locations along the Emilia-Romagna coast were chosen (Marina di Ravenna and Marina Romea) and the outputs from a multi-model ensemble used to generate 81 input combinations to be used as boundary conditions. The system provides a better assessment of uncertainty related to the incoming conditions providing additional information to the forecaster and for decision making.

CHAPTER 1 - FOREWORD

Among the several elements that are part of Early Warning Systems (EWS), forecasting services are of utmost importance as means to prepare for incoming extreme events. The quality of the forecasts that are issued relies on several aspects with one of them being how the system is set up for the intended applications and what type of information that specific system has to provide to the decision-makers in order for the best decision to be made on available time.

EWSs developed for coastal related activities are normally based on the implementation of hydrodynamic models that follow the Navier-Stokes equations with different approximations depending on the goals to be reached. For instance, small-scale applications aiming at reproducing total water levels with high precision and accuracy rely on good representations of currents, tides, and sea level propagating towards the coastline. However, hydrodynamic models alone do not account for morphologic variations near the coast, nor for the subaerial portion of the beach system. A further downscaling is normally required if coastal zone processes are to be accurately represented.

In this context, morphodynamic models calculate the hydrodynamic components, normally including waves, together with sediment transport in both the subaqueous and the subaerial beach. One example of such a model is XBeach (Roelvink et al., 2009), which has been initially developed to simulate the impacts of hurricanes on sandy beaches of the east coast of the United States following Sallenger (2000). With XBeach, the modeller can take into account the morphologic variation of the beach system under different incoming hydrodynamic and wave conditions.

At the Hydro Meteo Climate Service of the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna (Arpae-SIMC), a deterministic EWS based on the implementation of XBeach has been developed and is currently operational providing daily forecasts covering +72h. Using the outputs of XBeach in terms of maximum vertical water excursion, it is possible to calculate the distance between the water line and the closest infrastructure or dune. The closer the water is from such structures, the higher the chances of damage to the system.

As deterministic forecasts do not allow for addressing uncertainties, probabilistic approaches have been recently developed so the modeller and the decision maker have a better understanding on the predictability of incoming events. Moreover, the Italian Civil Protection Code itself (Legislative Decree no. 1 of 2 January 2018) provides for the transmission of forecasts in probabilistic terms. Hence, in the context of the STREAM project, the development of a probabilistic XBeach based coastal EWS has been conducted and the results are presented in the following subsections.

CHAPTER 2 - THE PROBABILISTIC COASTAL EARLY WARNING SYSTEM IMPLEMENTATION

2.1 PREVIOUS EXPERIENCES

As previously mentioned, at Arpae-SIMC there is already an implemented coastal EWS that runs operationally providing daily forecasts following a deterministic framework. The system follows an operational chain (Figure 1) that begins with the daily forecast of the meteorological models from the COSMO consortium (Steppeler et al., 2003) that provide the atmospheric forcing for the hydrodynamic model covering the whole Adriatic sea (AdriaC; Warner et al., 2010) and also for the wave model implementations based on the Simulating WAves Nearshore (SWAN; Booij et al., 1999; Ris et al., 1999) model. The outputs of AdriaC in terms of sea level and the outputs of SWAN in terms of wave parameters are then used to run XBeach and provide a single daily forecast for each of the implemented profiles.

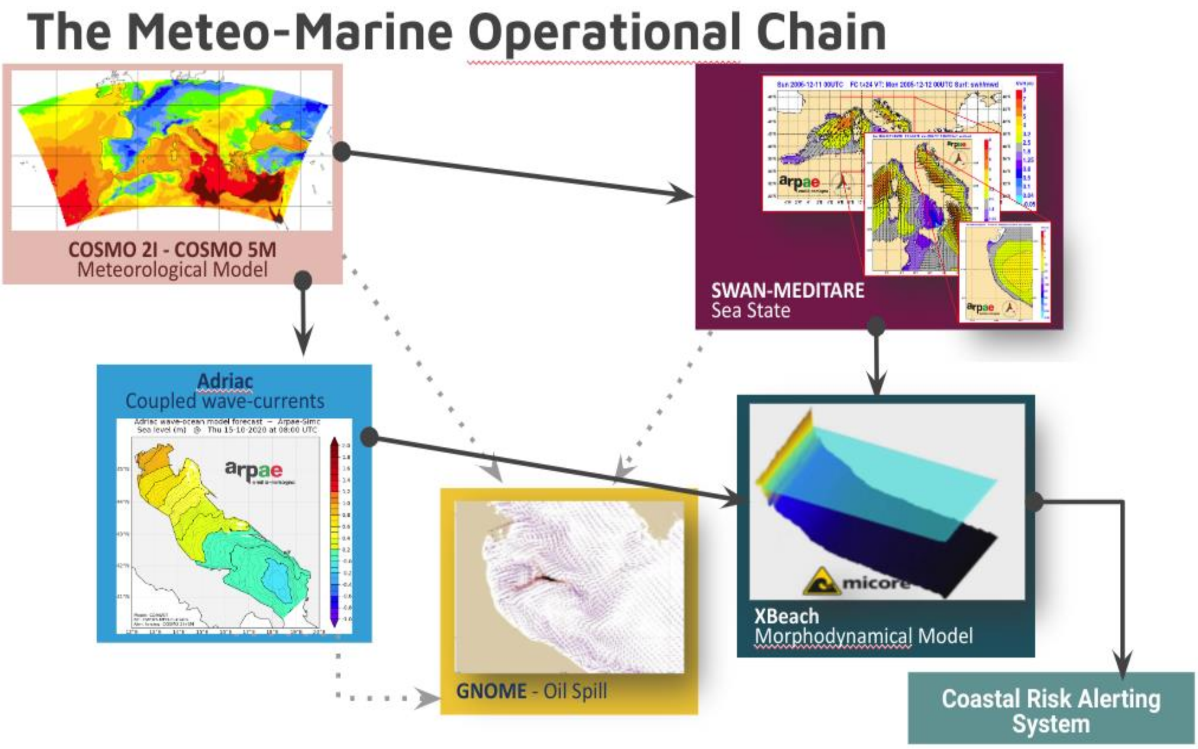


Figure 1: Hierarchical operational chain implemented at Arpae Emilia-Romagna.

Currently, the operational EWS is implemented in 12 locations along the Emillia-Romagna coast and the results are provided in terms of Storm Impact Indicators (SII) (Harley et al., 2016). For each profile, a landmark has been determined which can be a building in the case of urbanized areas or the dune toe for natural beaches. For the former, the distance between the waterline and the reference building is called the Building-Waterline Distance (BWD) while the latter is referred to the Safe Corridor Width (SCW) that comprehends the amount of beach available between the waterline and the dune toe. The BWD and the SCF are calculated for each forecasted time step and provide an indication of how far onshore the sea will arrive during the 72h hours. In Figure 2 it is possible to see an output of the implemented deterministic coastal EWS.

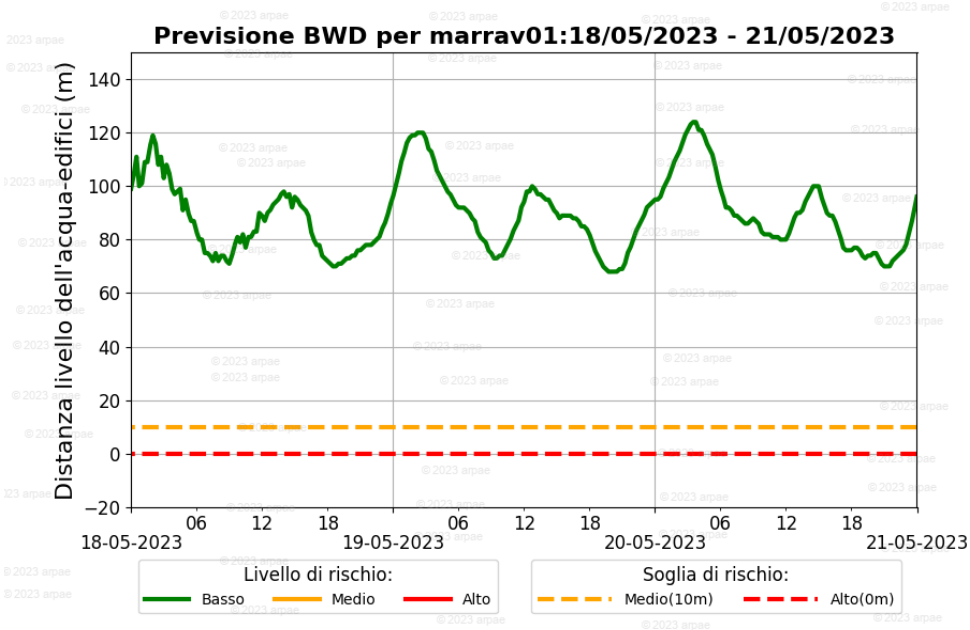


Figure 2: deterministic forecast already implemented at Arpae-SIMC

One of the previous experiences involving the migration towards a probabilistic EWS involved a (semi-)probabilistic application XBeach using the outputs of a multi-model ensemble system. The Transnational Multi-model Ensemble System (TMES) (Ferrarin et al., 2020) combines the outputs of five wave and six sea level forecasting systems and provides as outcomes the mean and standard deviation values for the sea level, wave period, direction and significant wave height. Through combining the TMES outputs in different ways and using them as boundary conditions for running XBeach it was possible to assess the uncertainty related to the incoming sea level and wave conditions as it is possible to see in the green shaded areas of Figure 3. More details can be found in the work of Biolchi et al. (2022).

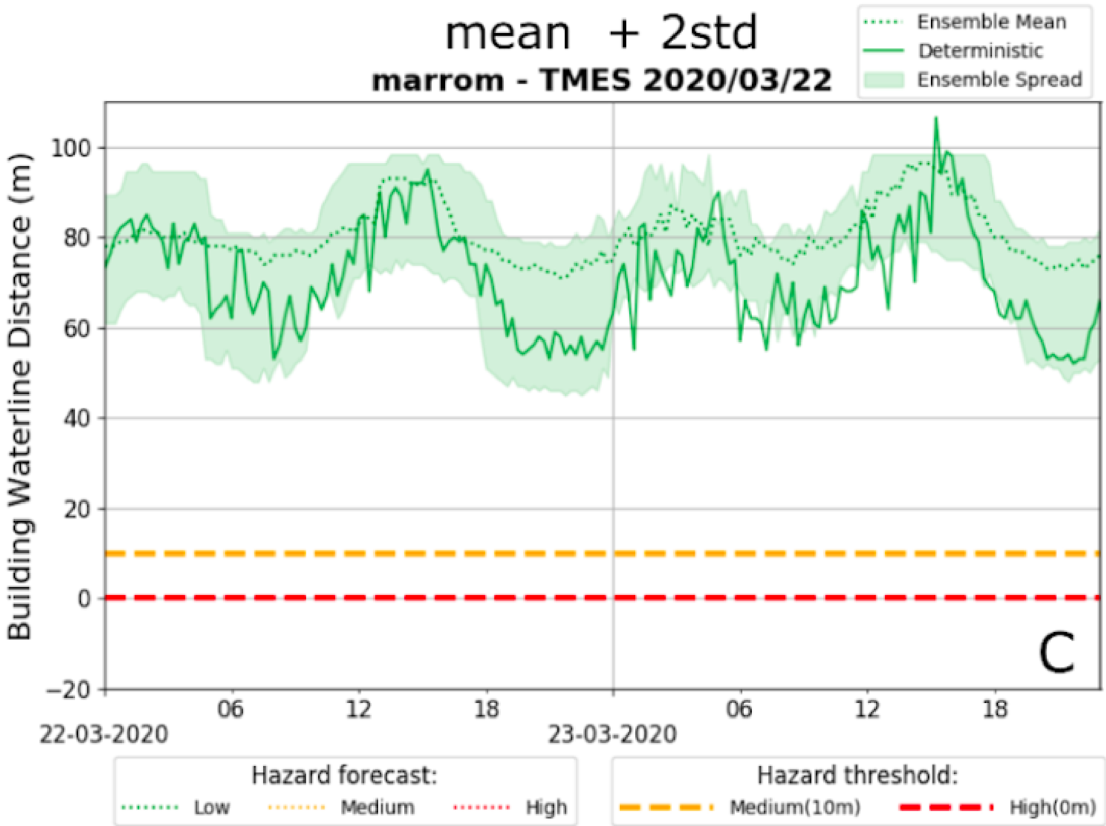


Figure 3: an example of the (semi-)probabilistic forecast that has been tested at Arpae-SIMC

Even with several limitations, the results of the (semi-)probabilistic implementation have indicated that a full probabilistic setting could provide more information and allow for a better understanding of the predictability of incoming extreme events. In this way, further work to be developed involved using a different set of combinations of the TMES results in order to achieve a larger number of forecasts. With more forecasts, it was then possible to calculate the percentage of members exceeding a given threshold which indicates a higher probability of incoming extreme weather events.

2.2 SELECTION OF PROFILES

The profiles chosen for the initial implementation followed what has been developed during the development (semi-)probabilistic version of the system. Marina Romea and Marina di Ravenna are areas where a mix between beach establishments and dune systems can be found and are located in the center-north portion of the regional coastline as shown in Figure 4.

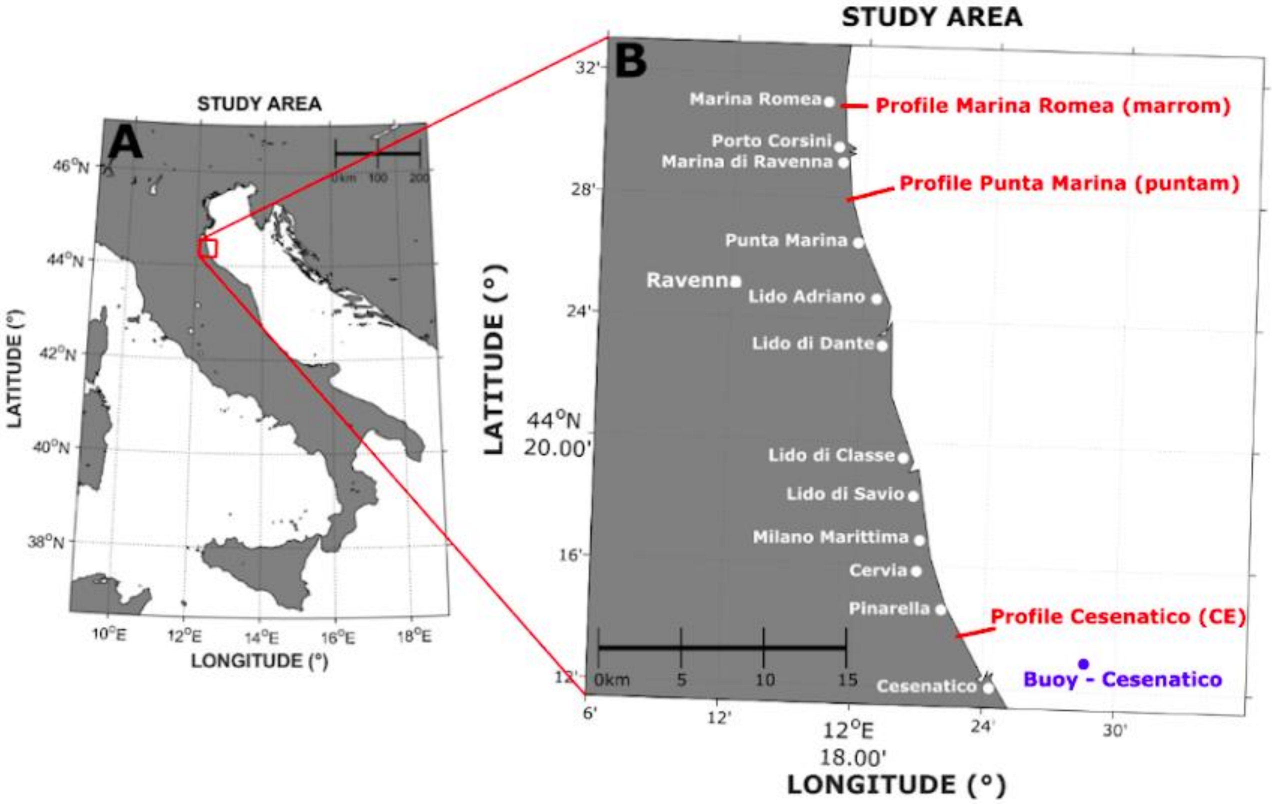


Figure 4: A) Situation map of the Italic peninsula highlighting the Tyrrhenian and Adriatic Seas with the red square covering part of the Emilia-Romagna coastline. B) Emilia-Romagna coastline showing some of the important regional coastal locations, the two transects (Marina Romea - MARROM - and Marina di Ravenna/Punta Marina - MARRAV/PUNTAM - used in the probabilistic implementation and the profile used for the calibration (Cesenatico) of the XBeach model

2.3 MODEL CALIBRATION

The calibration of the system followed what has been previously done for the implementation of the (semi-)probabilistic system (Figure 5). As an initial step, information was gathered about parameters and respective values to which XBeach was tested during applications in the Emilia-Romagna coastal areas. The investigated literature involved: Armaroli et al. (2013); Harley et al. (2011), (2016); Simmons et al. (2017), (2015); and Unguendoli (2018). Preference was given to ranges associated with better performances specifically in Cesenatico, as this is the location where the GLUE approach was applied.

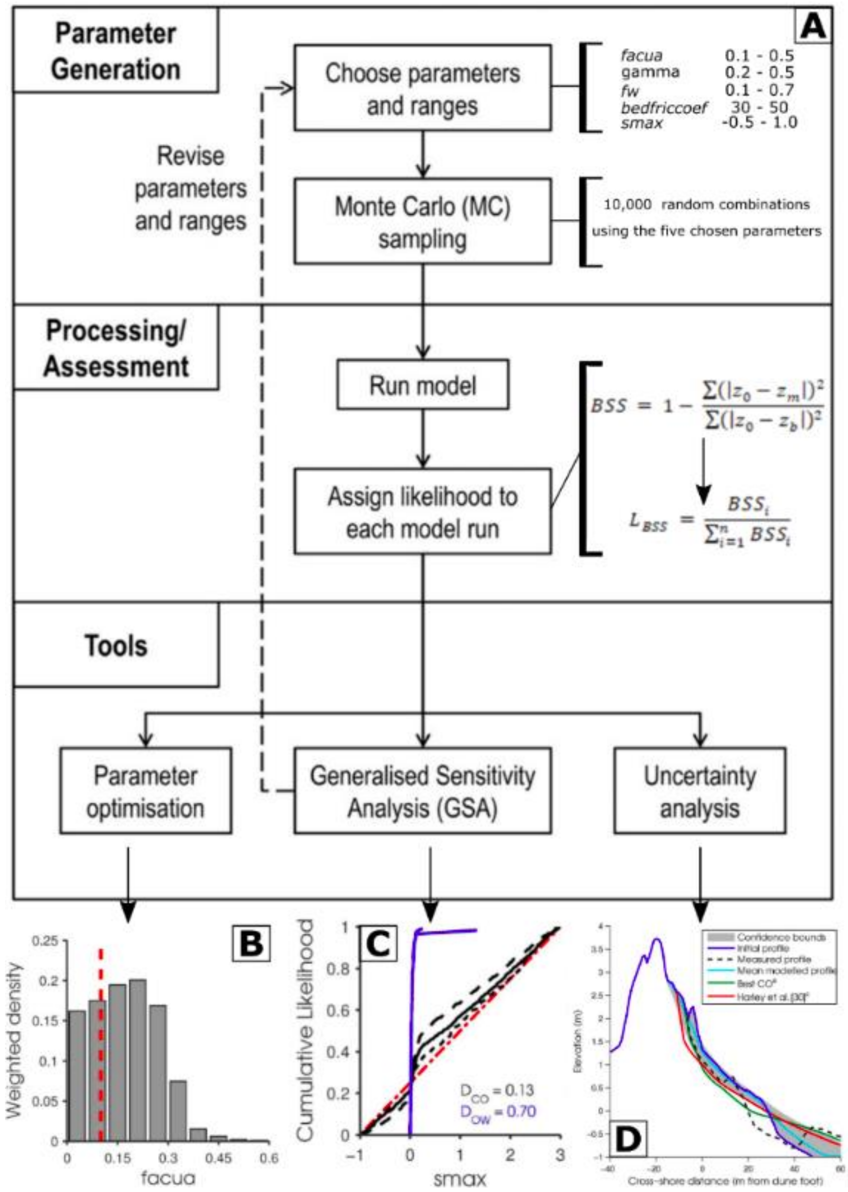


Figure 5: schematic representation of the steps followed to implement the GLUE approach. In subfigure A, the parameters and ranges used to generate the 10,000 sets of the first GLUE application are presented within the Parameter Generation box. The formulas used to calculate the model performance and the likelihood of each simulation are shown in the Processing/Assessment box in the same subfigure. After the simulations have been conducted, parameter optimization, sensitivity and uncertainty analyses were performed and examples of their graphical representations are shown in subfigures B, C, and D, respectively. All figures adapted from Simmons et al. (2017).

In a very synthetic way, 10,000 simulations were initially conducted with the initial parameter ranges collected from the literature. After that, a second set of 10,000 simulations was performed with a narrower range for the same parameters and substituting the one that has shown small or no influence in the simulations' outcomes. A more in depth explanation of the methodology and the results obtained can be found in the work of Biolchi et al, 2022. After the results of the calibration were defined and a final/optimal parameter range chosen, the probabilistic implementation was then carried out as explained in the following sections.

2.4 TMES BOUNDARY CONDITIONS

The (semi-)probabilistic implementation focused on adding or subtracting the results of the TMES in a very general way from all the input variables at the same time. As XBeach takes as an input three wave parameters (significant wave height, wave period and direction) and the sea-level, they used to be extracted from the TMES in terms of each variables' average and standard deviation. In order to have three different inputs, the variables' average constituted one of the boundary conditions while the other two forecasts would be conducted as follows: subtracting each variables' standard deviation from its average; adding one (or two) standard deviations to the mean. In this very broad way, uncertainties related to the boundary conditions would be incipiently addressed providing an initial idea on different outcomes that the system could have if the boundary conditions would be slightly different.

For the probabilistic implementation conducted in the context of the STREAM project, the approach was slightly modified in order to provide a larger number of boundary conditions. As the input variables were four, each one collected from the TMES in terms of average and standard deviation, they can be combined by adding/subtracting each standard deviation to the variables in different ways. For instance, the first member would be the average TMES sea-level, wave height, wave period and wave direction while the second member would be the average sea level, wave height, wave period and the wave direction plus one standard deviation. In this way, there are four variables being combined with three values each in different ways, totaling 34 = 81 as it is possible to see in the scheme in Figure 6.

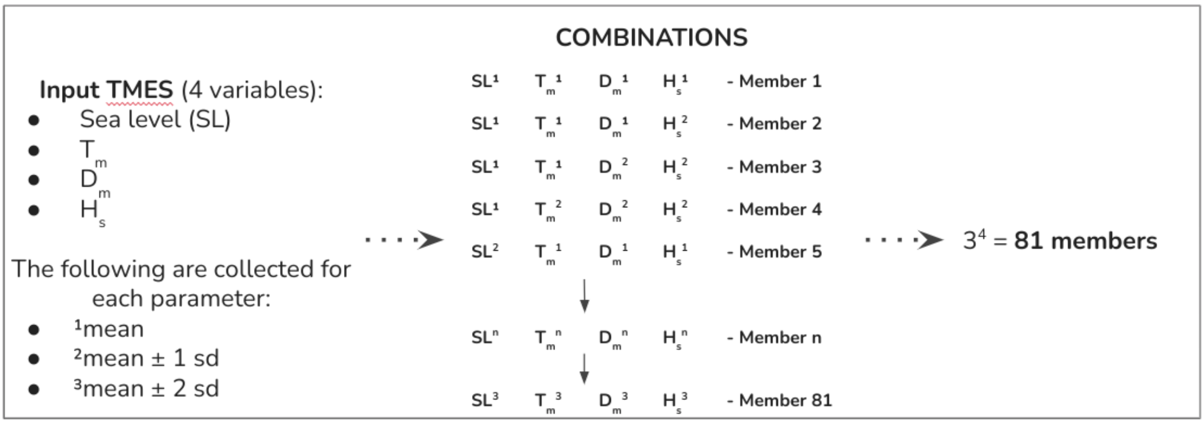


Figure 6: scheme of how the boundary conditions combining the average and standard deviation from the TMES were generated

For sea level, wave height and period the way in which the parameters are pre-processed is very straightforward. It involves using either the mean of these parameters or the mean plus one or two standard deviations as schematized in Figure 6. For the wave direction things change as, physically, adding one and adding two standard deviations creates a directional bias in the sense that it always adds a clockwise rotation to the values. Hence, to avoid the "always clockwise" rotation, it has been decided to add one standard deviation to some members (adding a clockwise rotation) and subtract one standard deviation (adding a counterclockwise rotation) to others in order to represent a range around which the waves could actually come from. This scheme can be seen in Figure 7. In Figure 8 it is possible to see a graph presenting the input (time series) for each variable for the forecast performed on the 25th May, 2023.

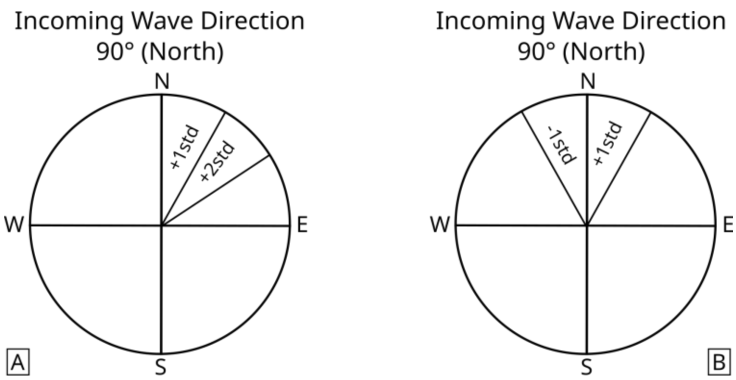


Figure 7: scheme of how the boundary wave direction has been pre-processed to generate the boundary conditions. A) Shows how the directional bias would be if the standard deviations were only added. B) Shows how the direction has been treated by adding and subtracting one standard deviation around the mean value.

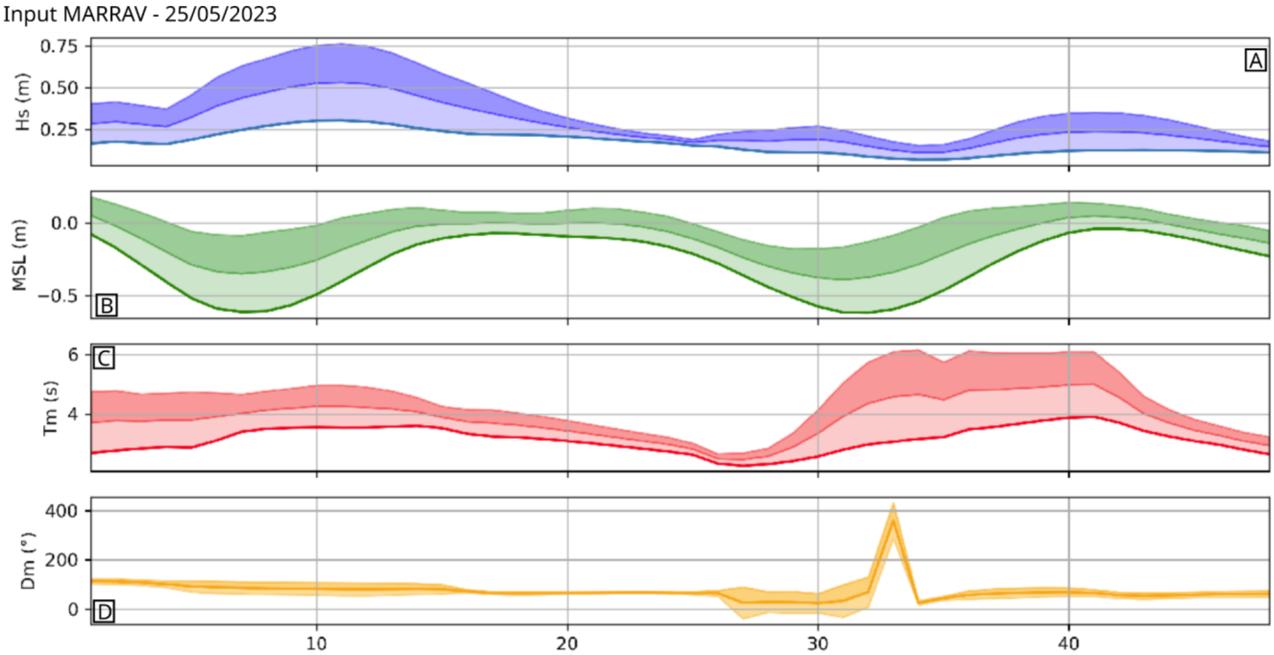


Figure 8: all the subfigures present the boundary conditions extracted from the TMES and used for running XBeach. They all cover +48h in terms of forecasted period and show, as the lower limit of the shaded areas, the average TMES value (average TMES minus one standard deviation for the direction), the average value plus one standard deviation as the line in the middle of the shaded areas (the average value in the case of the mean wave direction) and the average plus two standard deviations as the upper limit of the shaded areas (average plus one standard deviation in the case of direction). The variables presented in the plots are the following: A) significant wave height; B) Total water level; C) mean wave period; D) mean wave direction.

2.5 OPERATIONAL IMPLEMENTATION AND PRODUCTS

As shown in Figures 10A and 10C, the probabilistic outcomes of the implementation done during the STREAM project provide an initial idea about the oscillation of the outputs when slightly changing the boundary conditions that are propagated inside the XBeach model. In both figures it is possible to see the semidiurnal influence of the astronomic tide as the water levels rise and fall and the SII varies accordingly. The corresponding oscillation of the total water level can be seen in Figure 9B.

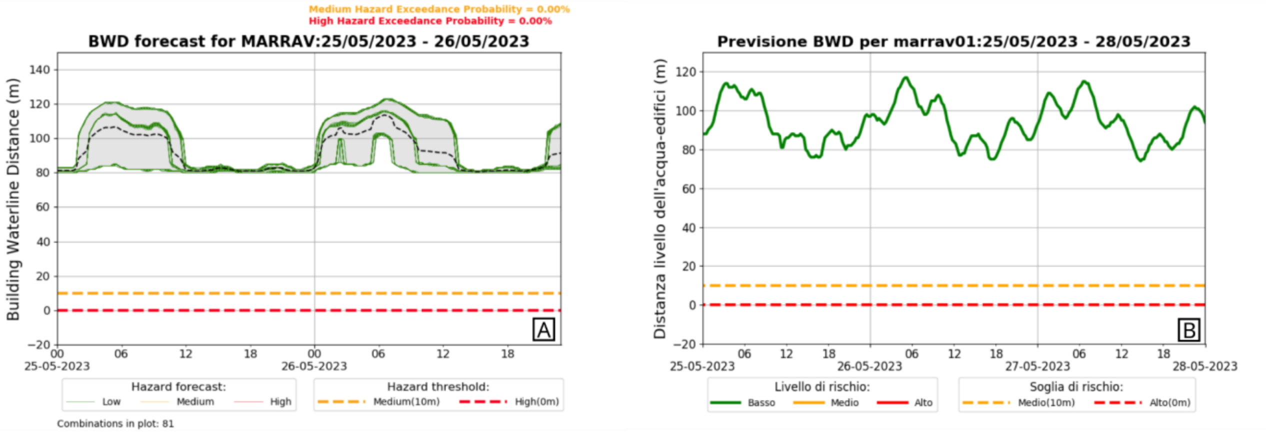
In the same plots of Figure 10, it is also possible to see that the members are combined in three major groups, following what is expected by having three different inputs for the sea level. The group constituting the bottom lines together represent the forecasts that used as boundary conditions the sea level plus two standard deviations. The group in the middle and the upper group correspond to the forecasts using the sea level average plus one standard deviation and the sea level average, respectively. This shows that the major controller of the vertical water excursion under relatively calm conditions is the daily/sub-daily water level variation (mostly regulated by the astronomic tides).

By having probabilistic forecasts (Figures 10A and 10C) and analyzing them together with the deterministic ones (Figures 10B and 10D) it is possible to see that small variations in the boundary conditions already provide quite large variations in the distance of the maximum vertical water excursion and the closest dune foot (as for both profiles the BWD is used as the SII). This is seen as the deterministic simulations provide a single forecast that varies between around 80m and 120m-140m. By the other hand, in the probabilistic forecast it is possible to see that due to a combination of different boundary variables the variations are already explicit while following the forecasted series. For instance, in Figure 10A around 6AM of the 25th May, 2023, the probabilistic forecast varies between 80m and 120m showing that slight fluctuations in the sea-level input could decrease the amount of dry beach available substantially, addressing in this way some of the uncertainties related to the boundaries.

The importance of the probabilistic forecasts becomes even more evident when the results are analyzed during a period with high incoming significant wave heights. In Figure 11, an interesting probabilistic forecast is shown in which, between 6AM and 6PM of May 16th, 2023, the forecasted waves were above 2m and the total water level also predicted high-incoming conditions. In the window previously described, it is possible to see the 81 members entangling each other which indicates an event of difficult predictability. In this particular case, the varied incoming conditions alter the morphological profile in ways that the feedback between the morphodynamics is apparent and affect the maximum sea level vertical excursion due to an interplay between waves, sea-level and morphological characteristics of the profile. Such situations show how important probabilistic forecasts can be as they provide an uncertainty measure and allow for more scenarios to be covered.

Finally, in Figure 12 it is possible to see the outputs of the model at Arpae’s internal platform (Infomet) which are made available to users from different categories to better understand the incoming morphodynamic conditions. The images are uploaded online on a daily basis.

Forecast MARRAV - 25/05/2023



Forecast MARROM - 25/05/2023

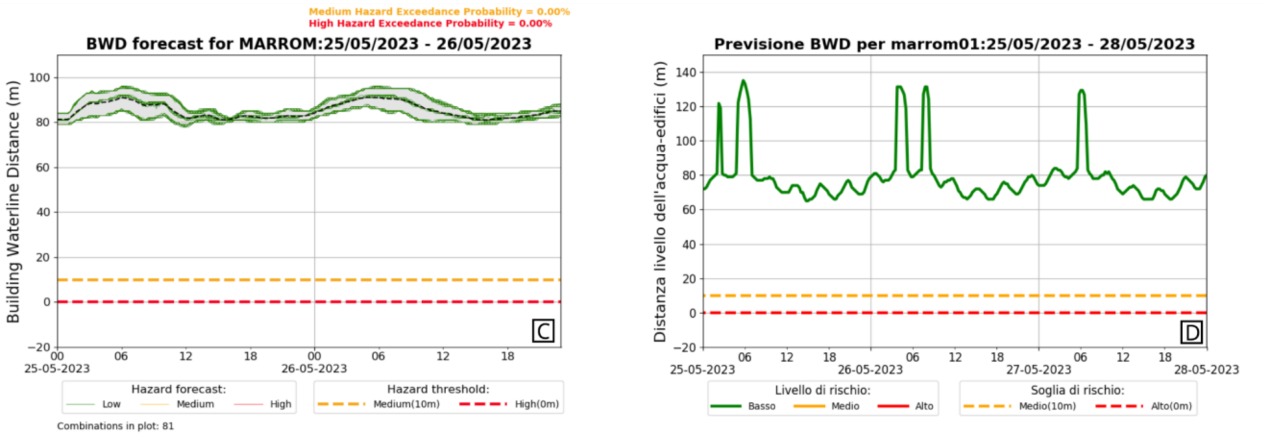


Figure 10: A) probabilistic forecast for the 25/05/2023 for the Marina di Ravenna (MARRAV) profile showing the 81 members of the ensemble. B) deterministic forecast for the 25/05/2023 for the Marina di Ravenna (MARRAV) profile. C) probabilistic forecast for the 25/05/2023 for the Marina Romea (MARROM) profile showing the 81 members of the ensemble. B) deterministic forecast for the 25/05/2023 for the Marina Romea (MARROM) profile.

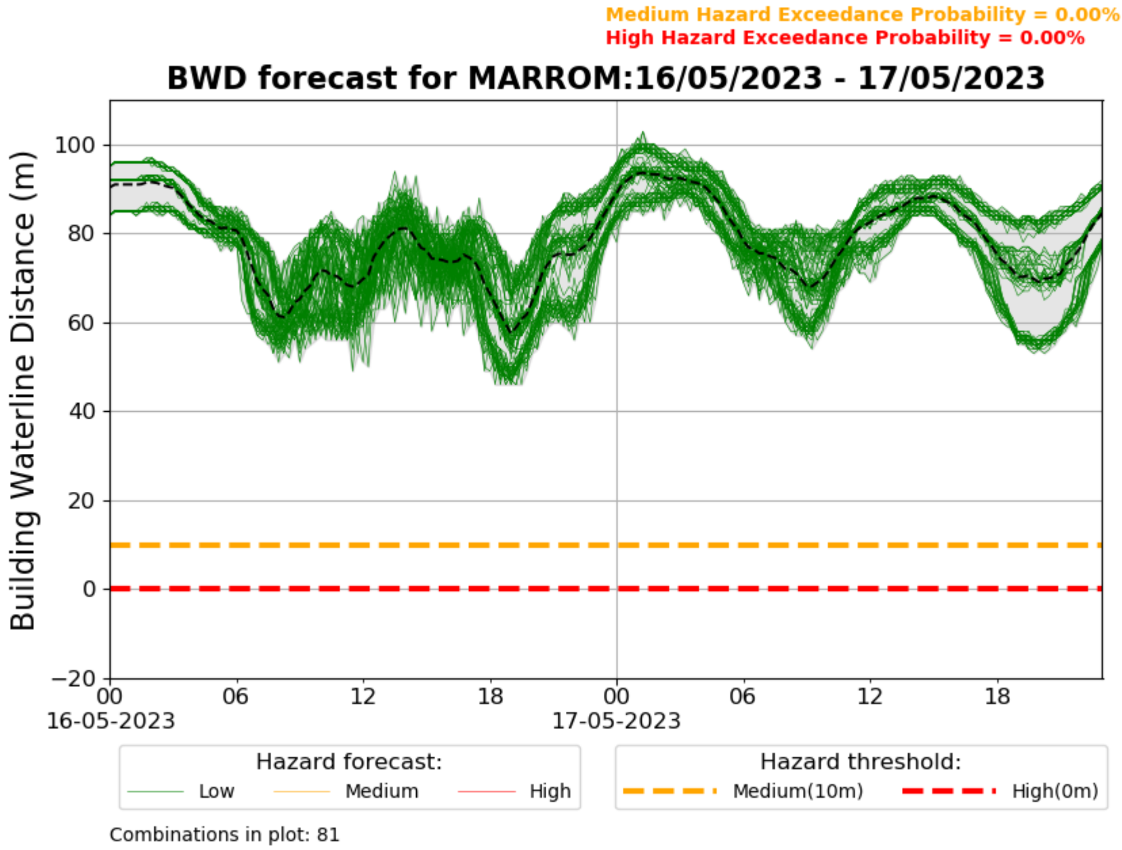


Figure 11: A) probabilistic forecast for the 16/05/2023 for the Marina Romea (MARROM) profile showing the 81 members of the ensemble

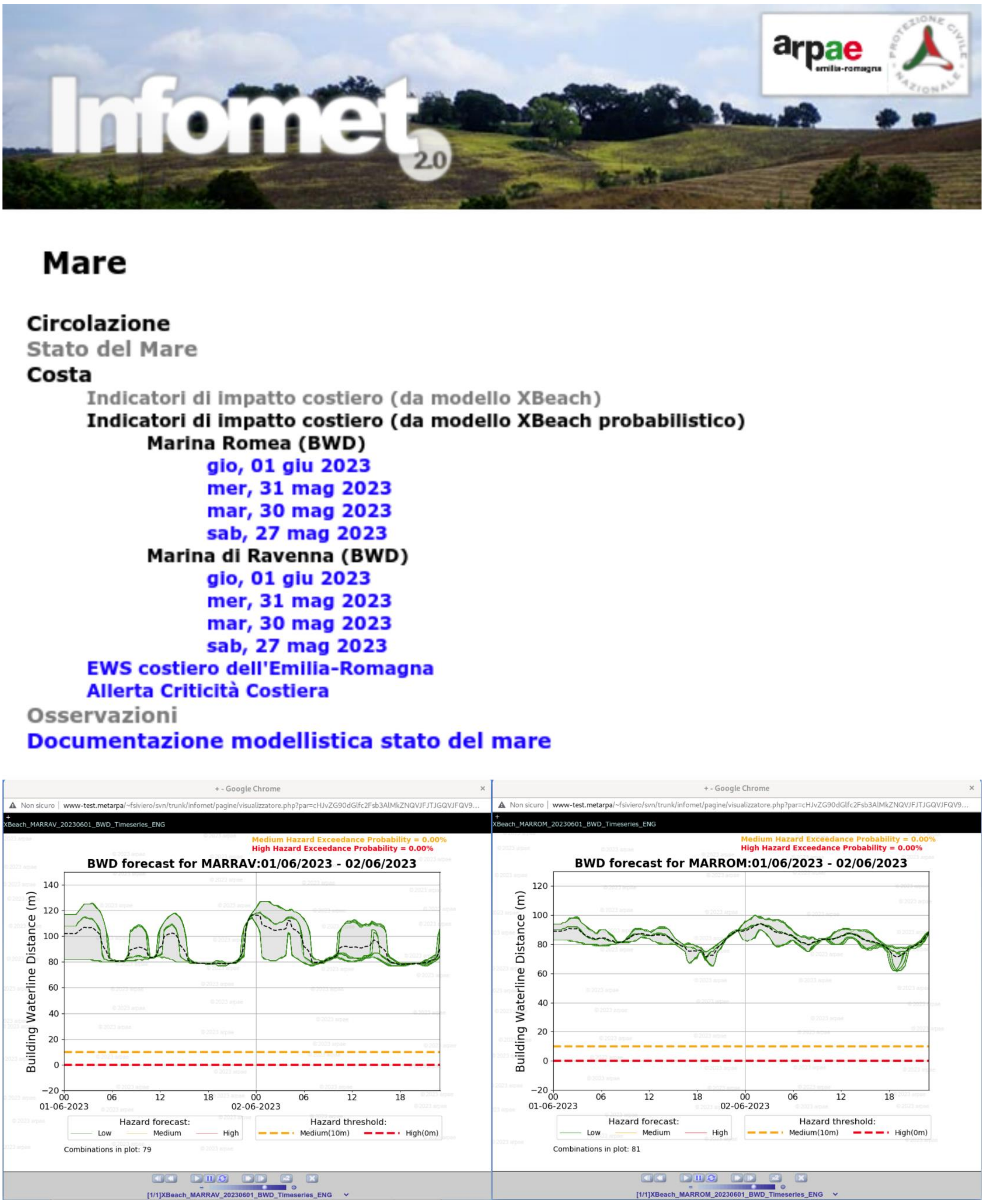


Figure 12: Example of the probabilistic forecasts being shown in Infomet

CONCLUSIONS

Deterministic approaches and probabilistic implementations of EWS can complement each other in providing information to forecasters and decision makers. By introducing the XBeach based probabilistic EWS for the coast of Emilia-Romagna, it is possible to address the predictability of events based on combining different values for incoming conditions collected from a multi-model ensemble. If analyzed together with the already existing deterministic EWS, the forecaster has a larger amount of information from which to base their decision. In the case of an incoming storm surge that overcomes the minimum alert thresholds, by having several members it is possible to indicate the probability of threshold exceedance, which quantifies in a way the possibility of the over than usual event taking place based on the total number of members.

One of the main constraints of the approach implemented throughout the STREAM project is still the lack of validation of the system. This can be achieved in the future by using the webcams which have also been installed during this project (see D.5.2.2. Webcams and 1 tide gauges station implemented, tested and data recorded). When the webcam data will be available and operational, the maximum vertical water excursion can be collected and used to check if both the deterministic and probabilistic XBeach implementations provide reliable measures of the conditions observed *in situ*.

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