EXTREME STORM SURGE AND WAVE HEIGHT ANALYSIS IN THE ADRIATIC SEA

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This study investigates the extreme storm surge and wave height in the Adriatic Sea. The joint occurrence of two different processes such as sea level (in terms of storm surge) and waves (in terms of wave heights) is analyzed. A copula-based approach was followed for the identification of the relation between the two datasets. Different couple of values of storm surge and wave height were provided, for different return periods, to assess coastal flooding risk or to design defence structures. Storm surge of about 1.5m is obtained in the northern part of Adriatic Sea for a return period of 100 years, and its associated wave height is provided.

Keywords: flooding; coastal defence structures; storm surge; wave height; bivariate analysis; Adriatic sea

INTRODUCTION

Many coastal phenomena, such as overtopping, loads on a structure and coastal flooding are the result of the combined actions of physical processes such as sea levels, waves, currents or winds. The most common cases are the combination of high sea levels and large wave heights and their joint occurrence.

Long-term sea level oscillations are basically caused by astronomical tidal and atmospheric forces. The tide level is composed by the astronomical tide and the meteorological tide. The meteorological tide (or residuals) is mainly caused by the forcing of i) pronounced air pressure disturbances and/or ii) strong winds: i) the air pressure variations induce an adjustment on the sea level which acts as an inverted barometer; ii) the action of wind on the sea surface is more complex, depending on the wind speed, direction, duration and on the topography of the basin.

The Adriatic Sea is a semi-enclosed elongated sub-basin (about 800 km long and 200 km wide) of the Mediterranean Sea. The basin is characterized by a broad and shallow continental shelf crossed by the Mid Adriatic Pit (maximum depth 280 m). The bottom deepens to the Southern Adriatic Pit, whose depth ranges between 180 m and 1200 m and rises again at the Otranto strait (780m). The western coast of the Adriatic Sea, except of the southern part, is smooth, isobaths run parallel to it, and depth increases gradually seaward. On the contrary the eastern coast is composed of many islands rising abruptly from the deep coastal water. A narrow shelf, with deep water relatively close to the shoreline, tends to produce a lower surge but higher and more powerful waves, while a wide shelf, with shallower water, tends to produce a higher storm surge with relatively smaller waves.

Therefore, given unique geomorphology, the Adriatic Sea plays a critical role in understanding the complex interactions between tides, storm surges, wave dynamics and, hence, it is subjected to significant environmental changes, especially in response to extreme meteorological events. The relationship between extreme storm surge and wave height has been the focus of numerous studies aimed at improving the predictive capabilities of coastal hazard models.

A fundamental aspect of the Adriatic Sea's dynamics is tidal resonance, a phenomenon where the natural oscillation period of the basin coincides with tidal forcing, leading to amplified tidal effects. The work of Medvedev et al. (2020) provides compelling observational evidence of tidal resonance in the Adriatic Sea, emphasizing its significant impact on local sea level variability. The study builds on previous research, such as the work of Cushman-Roisin and Beckers (2011) and Malacic et al. (2000), which laid the groundwork for understanding the tidal dynamics in the Adriatic, identifying key resonance frequencies that amplify the tidal range in specific areas of the basin.

Medvedev et al. (2020) confirm that the Adriatic Sea is particularly sensitive to this resonance due to its elongated shape and shallow depth, which enhance the interaction between tidal forcing and the natural oscillations of the basin. This sensitivity plays a crucial role in storm surge amplification, particularly during extreme weather events when the combination of meteorological forcing and resonant conditions can significantly elevate the sea levels. The interplay between tidal resonance and storm surges has been explored in detail by Cushman-Roisin et al. (2013), who demonstrated how storm-induced sea level rises are exacerbated by resonant conditions, particularly in the northern part of Adriatic Sea, where the geometry and the shallow water depth of the basin maximizes these effects.

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Understanding these interactions is essential for coastal management, especially in the context of climate change, which is expected to increase the frequency and intensity of extreme events in the Adriatic region. Studies such as Lionello et al. (2006) highlight the importance of incorporating both meteorological and tidal processes in forecasting models to better predict extreme sea level events. As the scientific community continues to refine its models, the insights provided by Medvedev et al. (2020) and related research offer critical guidance for improving the resilience of coastal communities along the Adriatic coast.

The importance of storm surge prediction in the Adriatic Sea cannot be understated, as it directly impacts coastal safety and urban planning in densely populated areas.

In recent years, the focus has expanded from forecasting storm surges to understanding the complex interactions between different sea level components. Bivariate statistical approaches have been increasingly applied to understand such interactions in marine environments, offering enhanced insight into joint occurrences of extreme events. This change has led to the adoption of multivariate statistical methods, which allow us to understand the interplay between extreme sea level components, such as storm surges, tides and waves. The work of Ragno et al. (2023) is particularly notable in this regard. Their investigation of extreme sea level events in both the Adriatic and Tyrrhenian Seas utilized multivariate analyses to unravel the complex relationships between climatic drivers and sea level components. They found that the co-occurrence of extreme meteorological and tidal conditions can significantly increase sea level extremes, further emphasizing the need for comprehensive approaches that consider these interdependencies when assessing coastal risks. Multivariate methods, as highlighted by Ragno et al. (2023), are crucial for advancing our understanding of how different environmental processes interact to produce extreme events. These approaches provide insights that can improve the accuracy of hazard models and support more effective coastal management strategies, particularly in regions like the Adriatic Sea, where the combined effects of storm surges, tides, and wave action pose significant threats to coastal infrastructure and ecosystems.

Coastal flooding is a complex phenomenon often influenced by multiple environmental variables. For both coastal management and engineering design, it is critical to account for the combined effects of different forcings. Two of the most significant variables to consider are the sea levels, driven by storm surges, and the wave heights occurring simultaneously with these elevated levels. In many cases, failure to address both aspects can lead to underestimations of the risks associated with extreme coastal events. This is particularly important in the context of climate change, where the frequency and intensity of such events are expected to increase. The aim of this study is to analyze these interrelated factors-â€”storm surges and wave heights to provide a more comprehensive understanding of their joint impact on coastal flooding risks. Through this approach, we seek to improve predictive models and contribute to more resilient coastal management strategies.

METHODOLOGY

The total sea level η is composed of several components: 1) the mean sea level, which can rise due to climate change; 2) the astronomical tides, driven by the gravitational forces of the moon and sun; 3) the meteorological tide, or storm surge, mainly caused by atmospheric pressure changes and strong winds during storms; 4) the set–up induced by the wave action.

1) The first contribution represents the long-term average level of the sea's surface. It can increase due to climate change, the likely global mean sea level rise by 2100 is between 0.28 to 0.55 m under the very low GHG emissions scenario (SSP1-1.9) and 0.63 to 1.01 m under the very high GHG emissions scenario (SSP5-8) Calvin et al. (2023).

2) The astronomical tide is due to the relative position between earth, moon and sun. It is a deterministic quantity that can be computed for each site location once the harmonic components and phases are known. By using harmonic analysis, the astronomical tide at a given location can be calculated as a superposition of sinusoidal oscillations, each one locally characterized by its amplitude and phase. The Adriatic tides can be well approximated by four semidiurnal (M2, S2, N2 and K2) and three diurnal (K1, O1, P1) harmonic constituents. Spreading of tides in the Adriatic is usually described by the largest M2 and K1 constituents. Semidiurnal tides have an amphidromic point halfway between Sibenik and Ancona. Diurnal tides are largest at Trieste and gradually decreases moving to the southern part of the basin toward Otranto, at the entrance to the Adriatic Sea Schwab and Rao (1983). In addition, a strong resonance is observed in the higher diurnal tidal frequencies, especially in the northern part of the sea, close to the basin head Medvedev et al. (2020).

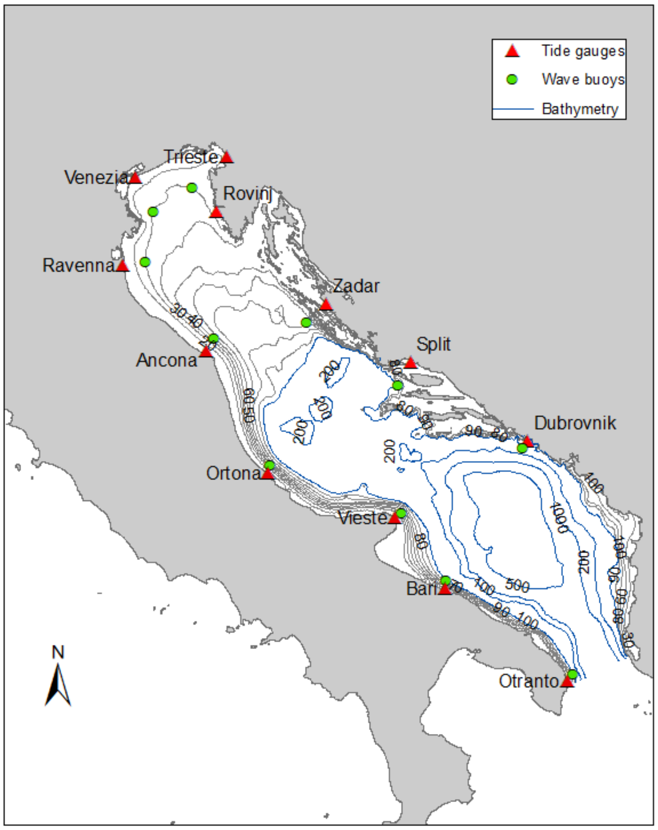

Figure 1: Locations of 12 tide gauges and wave buoys along the Adriatic Sea used in the present study.

3) The second contribution to tidal levels is given by the action of wind and barometric pressure on the sea surface during storm events. This contribution is usually referred as "storm surge". When an observed sea level (SL) is available, storm surge contribution as residual is usually computed as the difference between the observed SL and the astronomical tide. However, this definition can not adequately represent the meteorological contribution in case of large residuals due to the non-linear interaction between tides and surge which induces a phase shift in the tidal signal Williams et al. (2016). To account on this, an alternative method considers the "skew surge" as a better indicator for meteorological contribution de Vries et al. (1995). It is common to compute the skew surge as the difference between the maximum observed SL and the predicted high tide within a tidal cycle, independently of the time occurrence. This procedure allows the computation a single value of skew surge within a tidal cycle which is, by definition, lower than the maximum tidal residual. However, the authors highlight that this approach can lead to a strong underestimation of the skew surge values when the peak of the storm surge occurs in correspondence to the lower tide levels. To overcome this limitations, an hybrid approach is used in the present study, where the storm surge is computed as skew surge for the tidal phases around relative tidal maximal levels and as tidal residual around minimal levels. Therefore, two values of skew surge are computed within each tidal cycle: one during the high tide and the other during the low tide.

4) the last component of the total sea level η is due to waves. Short wave periods are in the order of 10s, approximately 4000 times smaller with respect to those of tides ($\approx 12h$). For design purposes, a typical sea-state is usually assumed to last for 3h Det Norske Veritas (2021) and it is represented by the significant wave height (H_s). For this reason, such parameter is used to consider the effect of waves. The waves during a storms induce an increase of the sea level which can be evaluated as the wave set–up.

Knowing the relation between such components is of primary importance for public institution, stakeholders and companies to assess coastal flooding risk or to design maritime defence structures.

Data collection

A dataset of tidal level and wave heights were reconstructed to perform the bivariate statistical analysis. In the multivariate analysis more informations are necessary in order to capture the dependence between variables, hence long dataset is needed.

The study made use of real tidal–level data recorder by 12 tide gauge stations located in Italy and Croatia as reported in Figure 1 (red triangle). The data were obtained from long–term sea–level records, with a temporal resolution of either 1 hour or 10 minutes and different duration.

Wave data from recorded by wave buoys do not cover a long overlapped periods, therefore, in order to maximize the dataset length, computed wave data were used. Wave data are taken from the wave reanalysis dataset of the Copernicus Marine Service (CMEMS: `https://data.marine.copernicus.eu/product/MEDSEA_MULTIYEAR_WAV_006_012`). This dataset is a multi-year wave reanalysis starting from January 1993, composed by hourly wave parameters at 1/24Â° horizontal resolution, covering the Mediterranean Sea and it includes an optimal interpolation assimilation scheme assimilating significant wave height along track satellite observations available through CMEMS. For each location, a point is chosen with the water depth equal to 30m and rather close the coast to ensure a correct representation of each site condition, see Figure 1 - green circle .

Extreme analysis of the storm surge

From the tidal level observed by the tide gauges the storm surge (SS) was computed once astronomical components are known Figure 2.

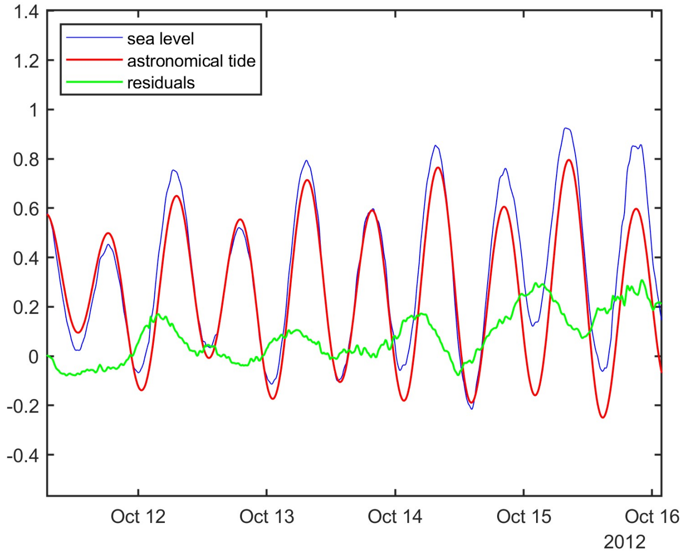

Figure 2: Sea level recorded by the tide gauges (blue line), astronomical tide (red line) and residuals (green).

To identify the contribution of storm surge from the tidal levels to each site, the astronomical components were subtracted from the sea level recorded by the tide gauges. As above reported, in order to consider the non-linear interaction between tides and surge, which induces a phase shift in the tidal signal, the skew surge is computed instead of the residuals. The storm surge, commonly named skew surge, is obtained as the difference between the maximum observed sea level and the predicted high astronomical tide, independently of the time occurrence. Such procedure were used for each maximum tidal cycle, while for each minimum tidal cycle the storm surge is computed as the difference between the sea level and the astronomical components. Therefore two values of storm surge were extracted for each tidal cycle.

Long datasets were obtained for each site. The peak-over threshold (POT) approach was applied to identify extreme events, according to a certain sea level threshold parameter u. The POT extreme surge values asymptotically follow the Generalized Pareto Distribution (GPD) family. For each group of events associated to a threshold, the shape (k) and scale (σ) parameters of the GPD are computed. The best threshold depends on the behavior of such parameters that show nearly linear trends. Larger values of the threshold were obtained by moving from South to North of Adriatic sea.

Peaks Over Threshold (POT) extreme values are extracted from time series by identifying clusters separated by a given time period. Data DECLUSTERING is performed to ensure that the events are independent which is required for the application of the corresponding extreme value distribution.

For each declustered set of storm surge peaks associated to a specific threshold, the following criteria were applied to choose the threshold:

- the *Mean Residual Life* (MRL) plot in which the mean observed excess over the threshold is plotted against the threshold itself. If the *Generalized Pareto* (GP) assumption is correct, this plot shows a linear trend Davison and Smith (2018);
- the trends of the shape (k) and scale (σ) (GP) parameters. A well-established practice Scarrott and MacDonald (2012) considers that the parameters tend to exhibit linearity up to a certain point, deviations from this behavior can indicate where the threshold should be set.
- the evolution of the *Normalized Root Mean Square Error* (NRMSE). A scatter in the NRMSE plot indicates that a lower threshold should be set.

The sampling step results in an independent multivariate sample of size N. $\lambda = N/N_y$ is the mean number of selected events per year, where N_y is the duration of the time series, in years. The size of dataset is matter to discussion. In the univariate case, a value of λ between 5 and 10, in order to have a sample size N above 100, depending on the duration of time series (typically 20 - 25 years in engineering applications). In the multivariate case, it can be argued that more information is necessary in order to capture the dependence between variables. Therefore it is suggested to increase the sample size, with a value of λ in the range 15 - 25, to be adapted to the duration of the available time series, to the site and to the physical processes under study.

Extreme analysis of the Wave height

The storm surge is assumed to be the main variable X. For each variable X, a statistical threshold u is set above which the N exceedances are modelled by a Generalized Pareto Distribution (GPD). A multi-distribution approach has been adopted for the second variable (Y), which is the wave height H_s, to check the better fit of other distributions (Weibull, Gumbel, etc.).

For coastal structures, flooding or overtopping will occur at large sea level. It is not necessary that all the variables be extreme: average wave heights occurring at an extreme sea level may cause coastal flooding, for instance. However, we define an event see Figure 3 when both storm surge and wave height exceed their threshold values. The chosen threshold value for the wave height (1m) is lower than that usually used in the Adriatic sea for monovariate extreme analysis of wave heights.

Such second value of threshold reduce the length of the dataset, however the value of λ is always larger than 10, with an average value of 15 for the different sites.

Bivariate Extreme analysis of storm surge and wave height

The joint occurrence of two different processes such as sea level X (in terms of storm surge SS) and waves (in terms of wave heights H_s) Y is analyzed. A copula-based approach was followed for the identification of the relation between the two datasets.

The procedure used is:

1. Data selection/Sampling of the joint time series for extreme analysis.
2. Modelling of marginal distributions of the storm surge (real data - tide gauge recordings) and wave heights (computed data - Copernicus Marine Service CMEMS)
3. Analysis and modelling of the dependence structure (SS, H_s).
4. Computation of joint probabilities and curves of joint return periods.

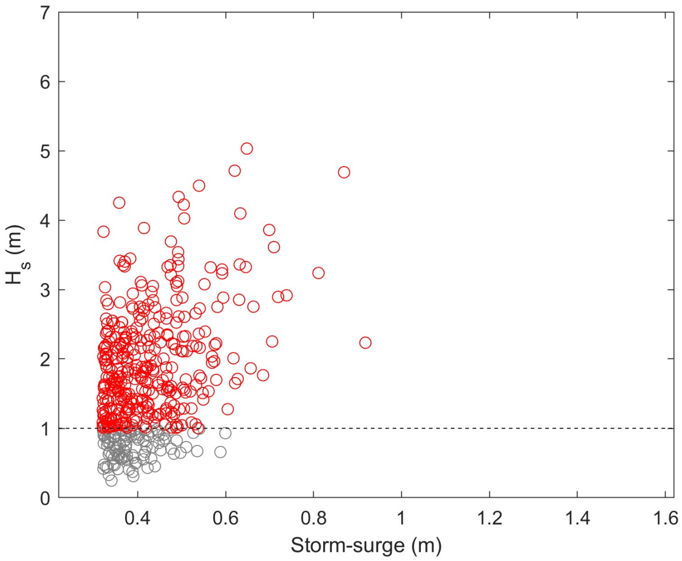

Figure 3: Comparison of the events by using both the threshold values (red data) and those by using only a single storm surge threshold (grey data).

The joint cumulative distribution function $H(x, y) = [Xx, Yy]$ can be linked to the marginal distributions of X and Y, F_x and F_y , via an extreme value copula C: $H(x, y) = C(F(x), F(y))$

Bivariate distribution of Storm Surge and Wave Height (H_S) for different Return Periods (RP) was performed.

The copula-based analysis requires a tool to describe and graphically represent the joint behaviour of the analyzed parameters. The most popular is based on the inverse Rosenblatt transformation and consists in the Inverse First-Order Reliability Method (IFORM) Winterstein et al. (1993). These contours are essential tools in offshore and coastal engineering, providing insights into the joint occurrence of extreme environmental conditions at specific return periods.

RESULTS

In this section the results obtained by performing the bivariate copula analysis were reported. In Figure 4 the environmental contours for the Ancona site are shown.

Each point along these contours has the same joint probability, meaning they represent equally likely combinations of storm surge and wave height associated to different RPs from 1 to 200 years. By analyzing the distribution of these points, we gain valuable insights into the relationship between these two variables. Specifically, we observe a trend where larger wave heights are typically associated with higher storm surge values. This is crucial for understanding how storm surge and wave conditions interact during extreme weather events.

A deterministic approach was applied for the selection of a pair of values of storm surge and wave height associated to each environmental contour. In the present study, along the environmental contour, the critical condition is chosen by assuming a condition of maximum flooding. The response of the system R is computed as the sum of two flooding contributions, see Figure 5: the wave set–up and the increase of the sea level S is given by:

$$R = S + 0.188H_s \tag{1}$$

as reported in Marini et al. (2022) for a planar beach with a slope 1:m. The coefficient 0.188 arises from the set-up definition of Bowen et al. (1968) computed at the shoreline.

Along each contour, the value of R is computed and the design condition is given by its maximum value. Repeating such procedure to different Return Periods, the red line in Figure 4 is obtained.

The same procedure was applied for the other sites. As shown in Figure 6, it can be noted that for the Venice site the environmental contours moves rightwards, while for the Dubrovnik site all the data are

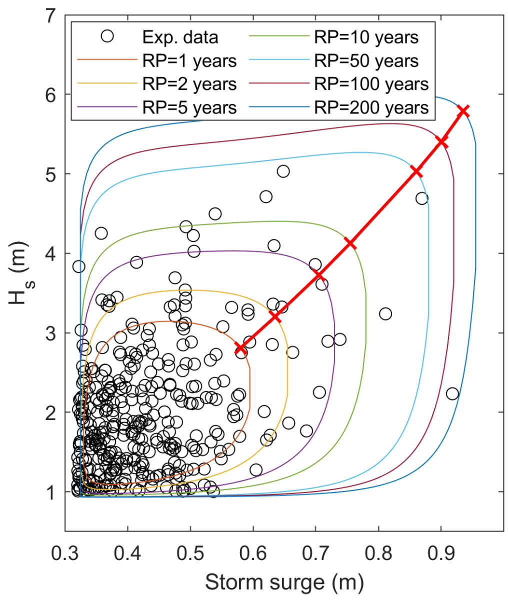

Figure 4: Environmental contours between storm surge and significant wave height computed for different Return Periods in the Ancona site.

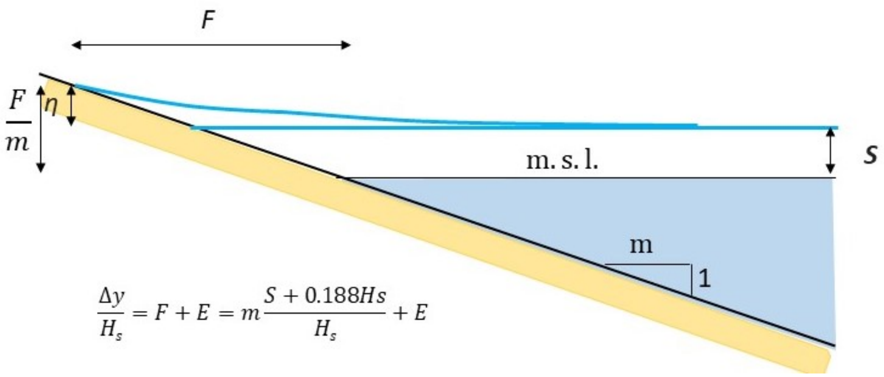

Figure 5: Flooding contribution in a planar beach.

restricted within a smaller range of storm surge values. Such results demonstrate the importance of storm surge for the Venice where a value of 1.5m for a return period of 100 years can be reached.

The procedure was repeated for all the other sites. Maps with storm surge and wave height countours evaluated for different return periods are provided, see Figure 7. Such results are obtained by assuming the coastal flooding as the main process. In the northern part of Adriatic Sea a larger storm surge is observed. For the same latitude the storm surge in the west part of the Adriatic sea is more significant with respect to the est side. The associated wave height is about 5m for a return period of 100 years.

Note the total sea level is composed by other components, hence at the storm surge and wave set up evaluated at a specific return period should be added the mean sea level (which can include the sea level rise due to the climate change) and the astronomical level.

A more complete analysis of the extreme total sea level in the Adriatic Sea is reported in Corvaro et al. (2025).

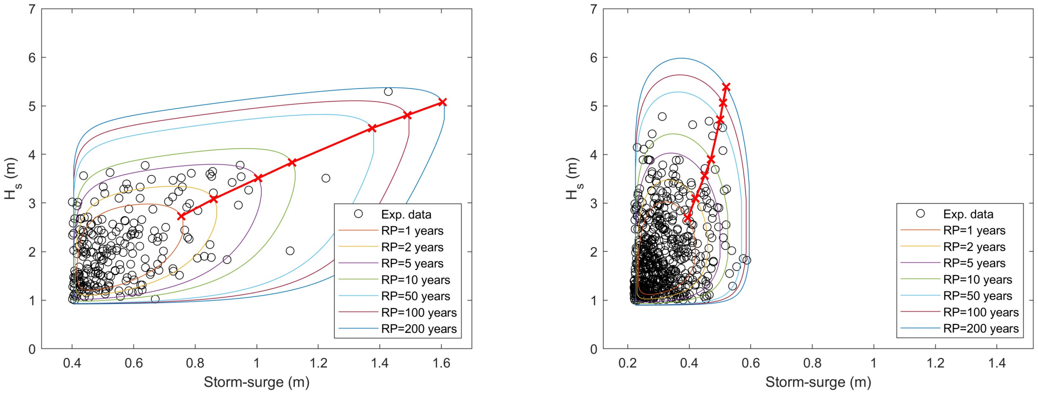

Figure 6: Environmental contours between storm surge and significant wave height computed for different Return Periods in the Venice site (left) and the Dubrovnik site (right).

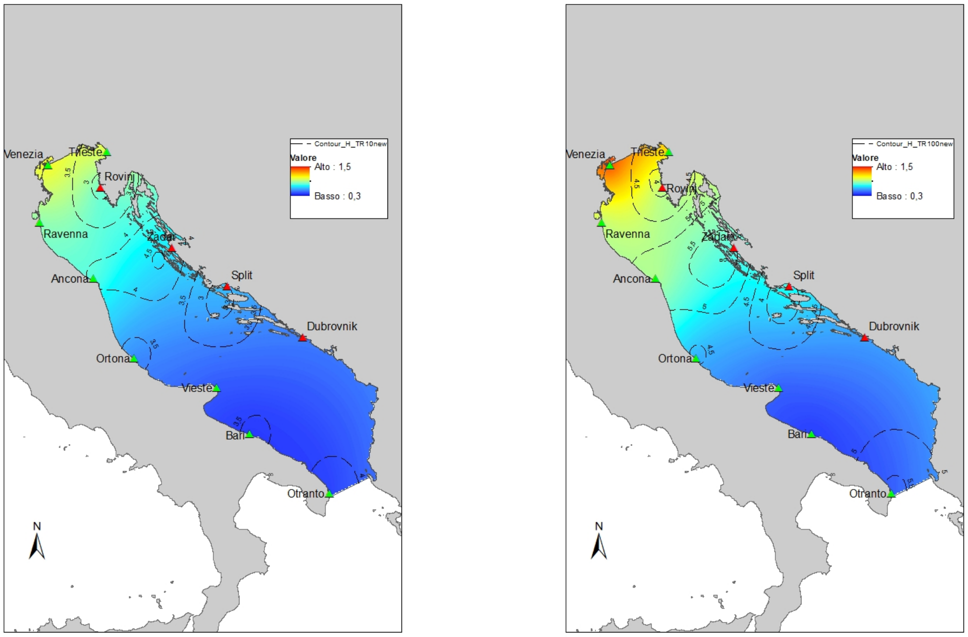

Figure 7: Storm surge maps and wave height contours in the Adriatic sea for different return periods: RP=10 years (left) and RP=100 years (right).

CONCLUSION

This study underscores the importance of employing bivariate statistical methods to assess the relationship between storm surge and wave height in the Adriatic Sea.

A maximum flooding condition has been proposed for sloped beaches and applied to select the values of joint occurrence of storm surge and wave heights along the environmental contour. A similar procedure can be applied for the design of coastal structures by using the maximum wave height and the associated sea level condition (storm surge) as critical condition for a specific return period. Maps of extreme storm surge and wave height are provided in the Adriatic sea for different return periods, by assuming the coastal flooding as the critical process. Storm surge is lager in the northern part of Adriatic Sea, reaching a value of about 1.5m in Venice for a return period of 100 years. The associated wave height is of about 5m.

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