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Investigating extreme sea level components and their interactions in the Adriatic and Tyrrhenian Seas

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ABSTRACT

Coastal hazards represent an existential threat to Italian coastal regions since they host important economic centers related to manufacturing and tourism. Knowledge of potential extreme sea levels (ESL), their component, and their interactions are essential to better evaluate potentially hazardous future extreme events in a changing climate and possible effects on the design of coastal structures. Hence, in this study, we investigate the interaction between tide and surge for extreme conditions of sea level in 9 locations along the Italian coastline facing both the Adriatic and the Tyrrhenian Seas and all in a semi-diurnal tidal regime. First, we introduce a novel dependence metric, i.e., the β factor, in support of the classical Kendall's τ to preliminary assess the effect of the dependence between tide and surge when conditioned on ESL on the variance of ESL, and then we quantify such effect using a copula-based framework. Here, the surge component is determined via the concept of skew surge, i.e., the difference within a tidal cycle between the maximum observed sea level and the predicted high tide (irrespective of the time of occurrence), to remove any random effect in the interaction due to the timing of the tidal peak. Our results show that ESL components, i.e., tide and skew surge, are negatively dependent, i.e., high/low values of the surge are associated with low/high values of the tide, in all the stations investigated, and that higher values of dependence, measured with Kendall's τ, can be observed in the Adriatic Sea, around -0.6, while lower values in the Tyrrhenian Sea, around -0.45, with the exception of Palermo. In general, an increase in ESL for higher quantiles is observed when the negative dependence between tide and surge is explicitly modeled. Moreover, our results show that the β factor can help quantify the relative contribution of tide and surge on the variability of ESLs. More specifically, small β refers to cases when tide and surge are similar in their magnitude, e.g., Palermo, while values of β close to 1 refer to the case when one component dominates the other. In the former case, ESLs obtained from a model that does not account for the dependence between tide and surge will result in ESL estimates with larger variability. On the other hand, when one component dominates the other, the variability of ESLs is slightly influenced by the model used for tide and surge, i.e., dependent or independent. We can then conclude that by explicitly modeling the dependence between tide and skew surge we can improve estimates and inference of ESLs.

1. Introduction

Sea level rise represents an existential threat to European coastal communities and their cultural heritage (Pörtner et al., 2022) and Italian coastal communities are no exception (Marsico et al., 2017; Di Paola et al., 2021; Schlumberger et al., 2022; Lionello et al., 2017). As a matter of fact, the Italian coastline stretches for about 8970 km and 28.2% of its population lives in coastal municipalities, i.e., municipalities directly facing the sea (ISTAT, 2022). Coastal regions are important economic centers related to manufacturing and tourism and today they are exposed to increasing coastal hazards (Antonioli et al., 2017; Pasquali and Marucci, 2021). The most famous and studied case is the city of Venice, a UNESCO heritage site, where events of *Acqua Alta*, i.e., high water events temporarily flooding the city, regularly threaten the city. Here, the event in November 2019 resulted in approximately 460 million euros worth of damages (Lionello et al., 2021a). Another example of coastal hazard occurred just a few months ago when high sea levels caused the overflow of river Pescara, a phenomenon known as backwater effect, inundating parts of the city of Pescara (Abruzzo region) (Zuliani, 2022). Interventions to improve the resilience of coastal

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regions to extreme sea level events and expected sea level rise have been addressed through different forecast, hindcast systems (Pasquali et al., 2015, 2019), and early warning system (De Girolamo et al., 2017). Other interventions have been progressively implemented such as the recently completed MoSE system in the Venetian Lagoon. At the same time, a thorough understanding of extreme sea levels, their components, and their interactions is still essential to better evaluate potentially hazardous future extreme events in a changing climate and possible effects on the design of coastal structures (e.g. Celli et al., 2018; Antonini et al., 2019)

Sea level (SL) can be decomposed into a tidal component, driven by astronomical forcing, a surge component, influenced by weather systems interacting with topography and morphology of the region, and mean sea level, i.e., the sea level when waves and tidal components are averaged out. Knowledge of potential extreme sea levels (ESL) is crucial when developing coastal protection strategies (Arns et al., 2020). Traditionally, ESLs have been mostly viewed in the context of storm surges (Haigh et al., 2011) since they were a significant factor in disasters such as the floods in 1953 (Horsburgh and Wilson, 2007) and the more recent event in October 2018 in the Ligurian Sea (Cavaleri et al., 2022). However, tides and the tide-surge non-linear interaction, i.e., a phase shift in the tidal signal induced by meteorological forcing and increased water levels (Horsburgh and Wilson, 2007), can strongly affect ESLs. Horsburgh and Wilson (2007) showed that, in UK estuary regions, large and locally generated surges are precluded close to high water. Zhang et al. (2010) showed via a numerical experiment that nonlinear bottom friction intensifies tide-surge interaction along the channel direction. In the Mediterranean, Marcos et al. (2009) mapped ESLs based on modeled data and observed that the nonlinear interaction between tides and surges is negligible. More recently, Arns et al. (2020) quantified the contribution of the non-linear interaction of tide and non-tidal residual on ESL at the global scale using a novel probabilistic approach and showed that ESL can be up to 30% higher if non-linear interactions are not accounted for. Similarly, Ferrarin et al. (2022) investigated the relative importance of different drivers of coastal flooding in the city of Venice and showed that even though storm surges are the main drivers of most ESL events in the lagoon, tides and long-term forcings associated with planetary atmospheric waves and seasonal to inter-annual oscillations played a predominant role in determining recurrent nuisance flooding.

The statistical analysis of the surge component, obtained when astronomical tide and mean sea level are removed from observed SL, often referred to as nontidal residuals, might not always be considered a representative atmospheric contribution to large residuals (Williams et al., 2016). Hence, a different metric *skew surge*, i.e., the difference within a tidal cycle between the maximum observed SL and the predicted high tide (irrespective of the time of occurrence) (de Vries et al., 1995) has been considered a better indicator for atmospheric contribution. Williams et al. (2016) analyzed tide gauge records spanning decades from the UK, U.S., Netherlands, and Ireland using the concept of skew surge and concluded that any storm surge can occur on any tide. On the other hand, Santamaria-Aguilar and Vafeidis (2018) analyzed 15 sites worldwide with a mixed semidiurnal regime and found that for approximately half of these sites, extreme skew surges occur more often during smaller high waters. This means that, in locations where a dependence between tide and surge is observed, the use of skew surge to quantify the surge component might not provide any advantage over nontidal residual.

Based on these premises, we investigate the interaction between tide and surge in conditions of ESL in 9 coastal cities along the Italian coastline facing both the Adriatic and the Tyrrhenian Seas and all in micro-tidal and semi-diurnal tidal regimes. Building on the previous work done by Arns et al. (2020) and Ferrarin et al. (2022) where tide and surge leading to ESL events were analyzed, we introduce a novel dependence metric in support of the classical Kendall's τ to preliminary assess the effect of explicitly modeling the observed dependence between tide and surge generating ESL on the variance of ESLs. Afterward, we quantify the effect of this modeling assumption on estimates of ESL using a copula-based framework. In this study, the surge component is derived via the concept of skew surge, to remove any random effect in the interaction between tide and surge due to the timing of the tidal peak.

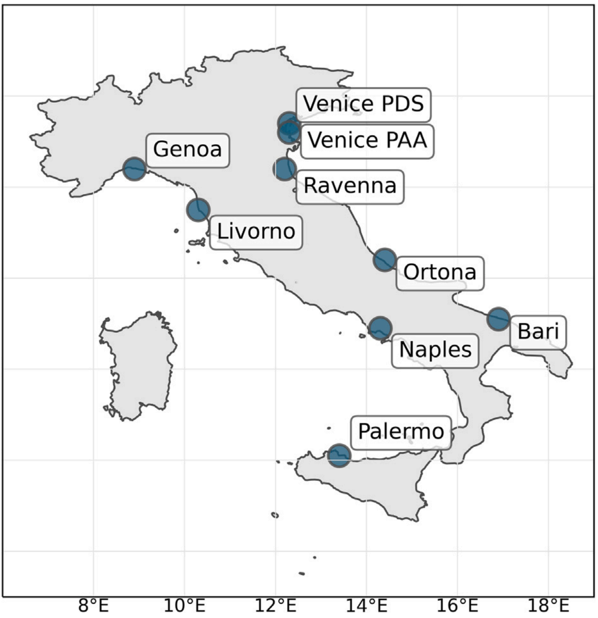

Fig. 1. Geographical locations of the tide gauges investigated in this study.

In the remainder of the paper, we first describe the locations investigated and their coastal dynamics. We then extrapolate from tidal-gauge observation ESLs and their components, i.e., astronomical tide and skew surge. Here, the former component is obtained via standard Harmonic Analysis. Afterward, a novel metric for assessing the dependence between tide and skew surge for ESLs is presented and a copula-based framework is applied to quantify the effect of tide-surge interaction on ESL for some interesting cases. Finally, a critical review of the results regarding the assumptions and methods implemented is provided.

2. Locations and data

The analysis is carried out considering 9 Italian coastal cities in which a tide gauge station is present and the data publicly available. More in detail, 5 stations are located in the Adriatic and 4 in the Tyrrhenian Seas.

The tide gauges of Ravenna, Ortona, Bari, Palermo, Naples, Livorno, and Genoa, belong to the “Rete Mareografica Nazionale” (Italian National Mareographic Network) and are commonly placed in confined waters (i.e. harbors). In the case of Venice stations, instead, the “Piattaforma Acqua Alta station” (hereinafter referred to as PAA) is located at the “Acqua Alta” research tower (Cavaleri, 2000), and is installed about 8 miles off the coast of Venice on a water depth equal to 16 m; the last stations, named “Punta Della Salute” (hereinafter referred to as PDS) is managed by the “Centro Maree” of the city of Venice and is placed on the “Canal Grande”, approximately in the heart of the historic city center. All the analyzed stations are located in the Mediterranean Sea, therefore the tidal regime is semidiurnal, the oscillations are of the order of centimeters and M_2 is the principal astronomical component (Tsimplis et al., 1995; Pugh and Woodworth, 2014). Fig. 1 summarizes the geographical locations of the mareographic stations used in this study.

We perform a careful visual inspection of the datasets and further quality checks to guarantee their accuracy. Some erroneous historical data are identified through a coherency cross-check among associated parameters within each record and removed as violating logical or physical relationships.

Considering that the geodetic reference is not the same for all the stations and the presence of subsidence in particular in the North Adriatic area, the annual Mean Sea Level is removed in each station record.

Moreover, according to the aim of the study, no pre-filtering actions have been applied to the data sets (i.e. raw time series have been used) in order to not alter the measures keeping the statistical characteristics of the sample unchanged. After validation, all the time series have low values in the percentage of missing/invalid values ranging from a maximum value of about 11% (Ravenna station) to a minimum value near 0% (both Venice stations).

3. Methods

3.1. ESL from peak-over-threshold sampling methods

Adaptation strategies are mostly driven by extreme natural events. Hence, we are interested in Extreme Sea Levels, i.e., ESLs. In this study, ESLs are obtained following the Peak-Over-Threshold (POT) sampling method (Coles, 2001; Antonini et al., 2019; Raby et al., 2019; Ragno et al., 2019). For each station, the threshold selection is based on the Mean Residual Life (MRL) plot, while the declustering time is kept constant and equal to 48 h for all the stations. Around 3 SL peaks per year are identified along the investigated locations. Once the ESL dataset for each station is defined, the corresponding datasets of tidal peak and skew surge are consequently determined as contributors to ELS.

3.2. Skew surge

The dominant mechanism for tide-surge interaction is that meteorological forcing and increased water levels induce a phase shift in the tidal signal, hence many properties of the synchronous residual component time series (difference between total sea level and tidal signal) are simply an artifact of small changes to the timing of predicted high water, (e.g., Williams et al. (2016) and Tiggeloven et al. (2021)). Therefore, the synchronous residual component is replaced by the metric *skew surge*, i.e., the absolute difference, in a tidal cycle, between the maximum value of measured sea level and the reconstructed high astronomical tide, without considering the time occurrence. The concept of *skew surge* was introduced by de Vries et al. (1995) to remove the correlation between tidal and non-tidal components induced by the timing of tidal peak.

In this study, to derive skew surge values from SLs we implement the following procedure: (i) decompose the total measured level in tide and non-tidal component via Harmonic Analysis (e.g. Codiga, 2011); (ii) identify high tidal peaks per tidal cycle, i.e., two peaks per day due to the semi-diurnal nature of the investigated locations; (iii) select the SL local maximum within a window of ±6 h around each tidal peak; if an SL local maximum is found (iv) calculate the skew surge as the difference between SL and tidal peak.

3.3. Quantification and modeling of dependence

To quantify tide-surge interaction at extreme sea level states, we first use the non-parametric rank correlation coefficient Kendall's τ, Eq. (1), which indicates the degree of ordinal association between two random variables, e.g., X and Y, (Kendall, 1938).

$$\tau = \frac{N_{cp} - N_{dp}}{N_p} \tag{1}$$

where N_{cp} and N_{dp} are the number of concordant and discordant pairs respectively, and $N_p = N_{cp} + N_{dp}$ is the total number of pairs. Here, a pair of the joint variables X and Y refers to (x_i, y_i) and (x_j, y_j) for $i < j$. The pair is said to be concordant if the order of x_i, x_j agrees with the order of y_i, y_j. Otherwise, the pair is said to be discordant. Values of τ close to $+1(-1)$ indicate a close positive(negative) association. To assess whether the dependence between two quantities is statistically significant, we use a two-sided hypothesis test where the Null-Hypothesis H_0 is the absence of association, i.e., $\tau = 0$. The level of significance of the test, α, is 0.05. The normal approximation is considered here meaning that the normal distribution with $\mu = 0$ and $\sigma^2 = 2(2n+5)/9n(n-1)$, where n is the number of samples in X and Y.

In the case of statistical dependence between two random variables, e.g., τ statistically significant, the dependence between variables can be modeled using dependence models such as copula functions independently from the distribution of X and Y, i.e., marginal distributions, Nelsen (2006), which are flexible tools also in higher dimensions (e.g. Morales-Nápoles and Steenbergen, 2014; Ragno et al., 2022). Let us consider F_x and F_y the marginal distribution of X and Y respectively, the joint distribution F_{xy} is defined as

$$F_{xy}(X, Y) = C(F_x(X), F_y(Y)) \tag{2}$$

where C is a bivariate function defined on the unit square $[0,1] \times [0,1]$ and it is uniquely defined (Nelsen, 2006; Salvadori et al., 2007). In this study, we consider empirical margins, e.g., F_x and F_y are the empirical cumulative distribution function (ecdf) of X and Y. We rely on the Akaike Information Criterion (AIC), Eq. (3), to select the parametric copula model.

$$AIC = 2(k - ln(L)) \tag{3}$$

where L is the likelihood function and k is the number of parameters in the copula model, which serves as a penalty factor to favor models with a smaller number of parameters. Among the available parametric copula models, the *best* model is the one with the smallest AIC. For the analysis, we use the Python library *pyvinecopulib* (https://github.com/vinecopulib/pyvinecopulib). Once the copula model is selected to best represent the dependence between the variables (X, Y), we generate 1000 pairs of (X_{dep}, Y_{dep}) and we compared their distribution with 1000 pairs (X_{ind}, Y_{ind}) generated independently from the independence copula, i.e., $C_{ind} = F_x(X) \cdot F_y(Y)$. In this study, the random variables X and Y are tidal peaks (TP) and skew surges (SK) the sum of which gives ESL, i.e., $ESL = TP + SK$. Hence, the comparison between the dependent and independent realization of pairs (TP, SK) sampled from copula models is done by comparing the ecdf of ESL in the case of independent random variables, i.e, $ESL_{ind} = TP_{ind} + SK_{ind}$, and in the case of dependent variables, $ESL_{dep} = TP_{dep} + SK_{dep}$.

To further quantify the effect of the dependence between tidal peaks and surges on ESL, we explore the relative contribution of ESL's components based on the properties of the sum of random variables. More specifically, let us assume two random variables X and Y with marginal distributions F_x and F_y, respectively, their sum $Z = X + Y$ is again a random variable with mean $\mu_z = \mu_x + \mu_y$ and variance $\sigma_z^2 = \sigma_x^2 + \sigma_y^2 + 2cov(X, Y)$, where $cov(X, Y) = E[(X - \mu_x)(Y - \mu_y)]$ is the covariance of X and Y. The covariance can also be expressed based on the Hoeffding's covariance identity (Hoeffding, 1940), Eq. (4),

$$cov(X, Y) = \int_{\mathbb{R}} \int_{\mathbb{R}} F_{xy}(x, y) - F_x(x) F_y(y)\, dx\, dy \tag{4}$$

Considering Eq. (4) the covariance can be interpreted as the distance of the joint model, i.e., F_{xy} in Eq. (2), from independence, i.e., the product of the two probability functions, $F_x F_y$.

If X and Y are sampled from their distributions independently from each other, the $cov(X, Y) = 0$ and the variance of their sum becomes $\sigma_{z,ind}^2 = \sigma_x^2 + \sigma_y^2$. If, on the other hand, X and Y are sampled in such a way that the correlation between them is preserved, the variance of their sum can be written as a function of the variance of the independence case, Eq. (5).

$$\sigma^2_{z,dep} = \sigma^2_x + \sigma^2_y + 2cov(X,Y) = \sigma^2_{z,ind} + 2cov(X,Y) \tag{5}$$

This brings us to the definition of the novel dependence metric, i.e., β factor, Eq. (6)

$$\beta = 1 + \frac{2cov(X,Y)}{\sigma^2_{z,ind}} \tag{6}$$

Based on this definition of β, Eq. (5) can be written as $\sigma^2_{z,dep} = \beta\sigma^2_{z,ind}$. Hence, β provides an indication of the effect of the dependence between two variables on the variance of their sum in absolute terms. This means that even if the two variables have a strong dependence when a rank-based metric such as Kendall's τ is considered, the actual effect on the sum of the variables might not be so relevant, especially if one variable dominates, in terms of its magnitude, the other. The closer the β factor is to 1, the smaller the contribution of the tide-surge interaction on ESLs will be. Thus, the β factor when used with a rank-based metric such as Kendall's τ provides an important preliminary understanding of where to expect changes, e.g., changes in the ESLs variance, and whether there is the need to explicitly model the dependence between two variables, such as in this specific study tidal peaks and skew surges.

4. Results

We analyze SL observations in 9 locations along the Italian coastline: 5 along the Adriatic Sea, i.e., Venice Punta della Salute (PDS), Venice Piattaforma Acqua Alta (PAA), Ravenna, Ortona, and Bari; and 4 along the Tyrrhenian Sea, i.e., Genoa, Livorno, Napoles, and Palermo.

After removing the mean sea level from every SL observation, we obtain ESL via the POT method. The results of the POT procedure, as well as the adopted threshold values are presented in Table 1. The resonant nature of the Adriatic Sea (Medvedev et al., 2020) is depicted by the identified threshold values. We observed higher SL in the north Adriatic Sea, where the threshold follows the modal shape of the fundamental 0th mode of the basin with maximum values of about 80 cm in Venice (north Adriatic Sea) to about 40 cm in Bari (south Adriatic Sea). The micro-tidal nature of the Mediterranean Sea is also explained by the smaller threshold values detected for the remaining stations that stay around 40 cm.

Fig. 2 shows the scatterplot of tidal peaks and skew surges resulting in ESLs for each station. The dots color's shades are normalized based on the range of ESL values, i.e., darker blue indicates higher ESL values compared to lighter colors. The dotted line indicates the threshold u adopted to sample peaks from sea level observations. From Fig. 2, it is clear that there is a negative correlation between tide and skew surge, i.e., high values of surge correspond to low values of tide and vice-versa when ESLs are investigated. Moreover, we can see that high values of ESLs are driven by high values of surges, i.e., blue dark dots are in general in the upper left corner of the plots where the surge takes a high value while the tide takes a mid to low value. On the other hand, in Ravenna, the highest ESL seems to be due to the combination of high values of the tide and high values of the surge, while Genoa and Palermo have the highest ESLs for high values of the tide and mid values of the surge. It is interesting to investigate further the maximum events recorded in the two stations in Venice. In Venice PDS the maximum event was the flooding event in November 1966 driven by meteorological conditions but relatively low values of tides. In Venice PAA the maximum event occurred in November 2019. This latter and most recent event was exceptional because the tide and the surge peaked almost at the same time, making it in nature different from the event in November 1966, Lionello et al. (2021b). However, such a difference in event type due to the timing of the peaks is not captured in our analysis since we quantified the surge by means of the skew surge. Fig. 2 shows also that the range of variability and the magnitude of surges and tides differ substantially. Hence, we further look into ESLs and the relative contribution of the tide and the surge to ESLs, Fig. 3.

Table 1
Number of years of observations (Num. Years), POT threshold values (u), and total number of selected peaks (Num. Peaks) for the investigated locations.

Station	u – cm	Num. Years	Num. Peaks	Av. Peaks per year
Venice PDS	81	97	316	3.3
Venice PAA	79	38	124	3.3
Ravenna	75	20	68	3.4
Ortona	55	22	75	3.4
Bari	47	21	67	3.2
Genova	40	22	72	3.3
Livorno	45	23	78	3.4
Napoli	39	20	70	3.5
Palermo	39	19	60	3.2

4.1. Contribution of surge and tide to total water level

In general, ESLs are greater in the stations north of the Adriatic Sea, i.e., Venice PDS, Venice PAA, and Ravenna, due to the Adriatic basin closed form, bathymetry, surrounding mountains (Bajo et al., 2019) and its natural mode of vibration (Medvedev et al., 2020). Here, tides and surges (that by definition in this work account for the seiches caused by the closeness between frequencies of the fundamental and first eigenmode of the basin and the frequency of the diurnal and semidiurnal components Medvedev et al., 2020) contribute almost equally to mean ESLs, while ESLs tend to decrease in the south of the Adriatic where the surges contribute to about two third of mean ESL due to smaller amplitudes of the tidal component, Fig. 3(a). Overall the resonant nature of the Adriatic Sea is fundamental for understanding the relative contribution of tide and surge to ESLs. In fact, we can clearly see the reduced importance of the tide levels by moving from the northern to the southern part of the basin. The Tyrrhenian stations, as expected due to the minor tidal ranges, clearly show the dominant contribution of the surges to the ESLs, with the exception of Palermo, where the tide and the surge seem to contribute equally, Fig. 3(b).

We are interested not only in the relative contributions of tide and surge to ESLs but also in their dependence. From Fig. 2 it is evident that tide and skew surge are negatively dependent, i.e., high/low values of the surge are associated with low/high values of the tide. We quantify the tide-surge dependence using Kendall's τ and we observe a statistically significant dependence ($\alpha = 0.05$) in all the stations investigated, ranging from −0.44 (Genoa) and −0.67 (Palermo), Fig. 4(a). We detect higher values of dependence in the Adriatic Sea, around −0.6, while lower values in the Tyrrhenian Sea, around −0.45, with the exception of Palermo. Such a result is expected due to the shallow nature of the Adriatic Sea in which surges occurring at high tide tend to be damped while surges occurring at rising tide are amplified as already worldwide observed by Arns et al. (2020) in their investigation on the non-linear tide surge interaction. However, from a preliminary sensitivity analysis, we noticed that the strength of the rank-based dependence increases when higher thresholds of ESLs are considered. This could be explained by the fact that the dependence is to a certain degree induced by the sampling approach adopted, i.e., tide and surge are selected conditioned on ESLs meaning that their sum must be higher than a predefined threshold. Hence, we further investigate the relationship between tides and skew surges to better understand their contribution to ESL. We calculate the novel dependence metric defined in Eq. (6), the β factor which is not rank-based but accounts for the magnitude and the range of variability of the two contributing factors, i.e., tides and skew surges, Fig. 4(b). The β factor ranges from 0.26 and 0.38 in the Adriatic sea, indicating that along the Adriatic coast, the expected variability of ESL is quite significant since the variance of ESLs is roughly 1/3 of the variance expected under the assumption of independence between tide and surge for extreme conditions of SL. In the Tyrrhenian Sea, the β factor ranges between 0.4 and 0.6 indicating a smaller contribution of the tide-surge interaction on ESLs, with the exception of Palermo. Here, we obtain a β factor of 0.2 meaning that tide-surge interaction plays a

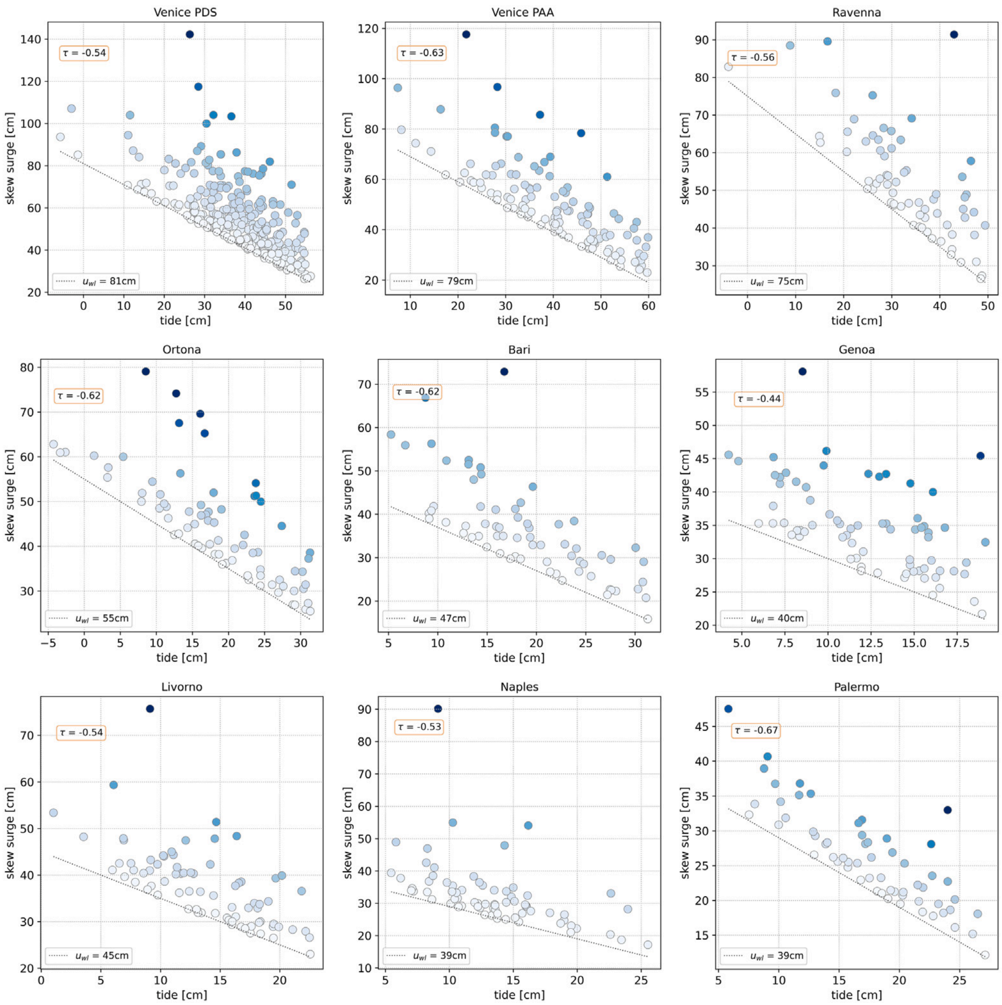

Fig. 2. Scatter plots of tide and skew surge conditioned on ESLs. The shading blue colors are proportional to the range of magnitudes of SL, i.e., the sum of tide and skew surge, in each station. Dark blue indicates the highest ESLs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

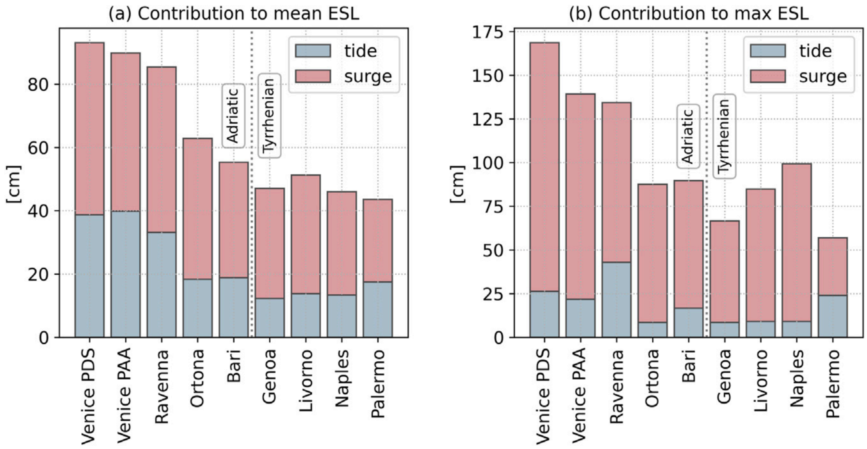

Fig. 3. Relative contribution of the tide (blue) and the skew surge (red) to ESL. Panel (a) is relative to the mean value of ESL, while panel (b) is relative to the maximum ESL recorded. By comparing panel (a) and panel (b) we can observe the increasing contribution of surges to higher ESLs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

major role in ESLs. This can be explained by the relative contribution between the two components. As a matter of fact, Fig. 3 shows that skew surge and tidal peaks have very similar magnitudes and range of variability and contribute almost equally to both average and maximum ESLs.

To further show that the β factor is a good indicator to evaluate the need to explicitly model the dependence between tide and skew surge and improve ESLs inference, we apply the theory of copulas to 4 stations, Venice PDS, Genoa, Naples, and Palermo. The best theoretical model is chosen among the available copulas in the Python

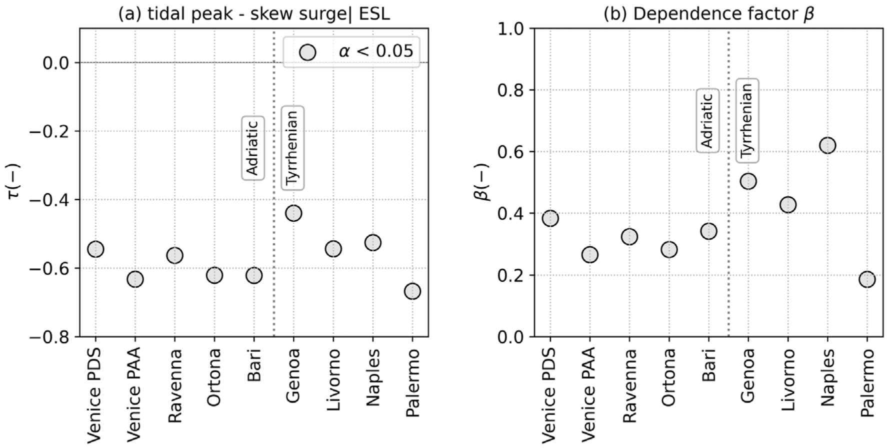

Fig. 4. Quantification of the dependence between tide and skew surge via two different metrics: (a) Kendall's tau on the and (b) the novel β factor.

package *pyvinecopulib* and it is the one with the smaller AIC. In all the stations, the theoretical copula selected is the Transformation local likelihood kernel estimator (TLL). Hence, we also report the second-best parametric copula model which is either the Gaussian copula or the Student copula. Both copulas are symmetric but the Student copula presents tail dependence, i.e., a stronger association at the tails, while the Gaussian copula does not have tail dependence, Salvadori et al. (2007). Fig. 5 shows a comparison between the cdf of ESL estimated considering a dependence model, i.e., TLL copula (black solid line) and Gaussian/Student copula (green dashed line), and the independence model, i.e., the independence copula (solid red line); gray dots represent observed ESLs. An increase in ESLs for higher quantiles, around 10% for the 80th quantile, is observed when considering the independence model compared to the dependence model, in accordance with previous studies (Olbert et al., 2013). Moreover, we can see the divergence pattern between the independent and the dependent model, i.e., the solid red line diverging from the solid black line. If we compare the stations of Venice PDS and Naples, which have very comparable Kendall's τ values, we can appreciate the effect of choosing a model that explicitly accounts for the dependence between tide and surge on the variability of ESLs. In Venice PDS we observed a reduction of the variability of ESLs greater than in the case of Naples, i.e., the solid red line starts to diverge at lower quantiles, Fig. 5. This type of information is not contained in Kendall's τ metric but it is evident in the β factor. As a matter of fact, the β factor in Venice PDS is smaller than the β factor in Naples, 0.38 and 0.62 respectively, meaning that the reduction of variability of ESLs due to tide-surge dependence is greater in Venice PDS than in Naples. The case of Palermo is also very interesting since the effect of the dependence is quite evident compared to the other stations. However, the level of dependence quantified via Kendall τ is similar, i.e., -0.67 in Palermo versus -0.54 in Venice PDS, while the β factor hints at other sources of changes due to the tide-surge interaction. In this specific case, the low value of the β factor in Palermo (0.19) can be explained by the fact that the magnitude and the range of tides and surges are similar, i.e., the surge variability is just about 60% higher than the tide variability, while in Venice PDS this variability is more than double and the surge component slightly dominates the tide component.

5. Discussion

We analyzed the interaction between pairs of tide and surge generating ESLs. The observed dependence cannot be generalized to all sea level conditions since the analyses performed are tight to the subsample investigated, i.e., ESLs. This, however, does not affect the validity of the results obtained. Here, we showed that tide and surge can compensate one another in generating sea level extremes, and, by considering their joint occurrence, it is possible to improve the estimate of ESLs, especially in terms of their variability. The assumption that all surges can occur at any tides, regardless of their dependence when extreme sea levels are of interest, can lead to an overestimation of the variability of ESLs and so misleading estimates of the worst-case scenario. Hence, by investigating tides and surges and their dependence it is possible to have a better understanding of their contribution to generating extreme sea levels. In this context, the β factor introduced in this study can hint at the extent to which the interaction between tide and surge affects ESL variability, information that cannot be inferred via traditional rank-based dependence coefficient such as Kendall's τ. More specifically, small β refers to cases where the contribution and the variability of the two components are similar, e.g. Palermo. On the other hand, β reaches values close to 1, i.e., the variance of the independence case is very similar to the variance of the dependent case, when one variable dominates the other. This is important when assessing flood hazards in future climate scenarios since a thorough understanding of the changes in the individual components is necessary. In fact, if a reduction in storminess, and so a reduction in the surge component, is expected tide-surge interaction might increase. Vice-versa if surges are expected to increase in future climate tide-surge interaction might become less relevant for flood hazard assessment.

We adopted the notion of skew surge to quantify the component of sea level induced by meteorological conditions. This assumption was driven by the desire to remove a spurious correlation given by the random timing of the surge's peak and the tide's peak that cannot be attributed to the interaction between the two components. In fact, when decomposing observed ESLs, many properties of the synchronous residual component time series (difference between total sea level and tidal signal) are simply an artifact of small changes to the timing of predicted high water (Williams et al., 2016). Moreover, in this study, we did not investigate the time shift between the tide and surge peaks but we restricted the analyses to observed ESLs and the combinations of tide and surge leading to those extremes. In this case, the magnitude of the two components and their relative interaction was important. For this, we decomposed ESL's observations so that the magnitude of the tide peaks was preserved to avoid an underestimation of the tide component and a consequent overestimation of the surge component.

We developed a copula-based model to further investigate the dependence between tide and surge. The advantage of this modeling approach resides in the possibility of generating larger samples and extrapolating events. However, the choice of the copula family can affect the discrepancies between the assumption of dependence or independence between tide and surge, e.g., the difference between the solid black line and the dotted green line, Fig. 5. Hence, the choice of the theoretical model requires attention beyond the traditional goodness of fit metrics such as AIC. Moreover, multivariate models might

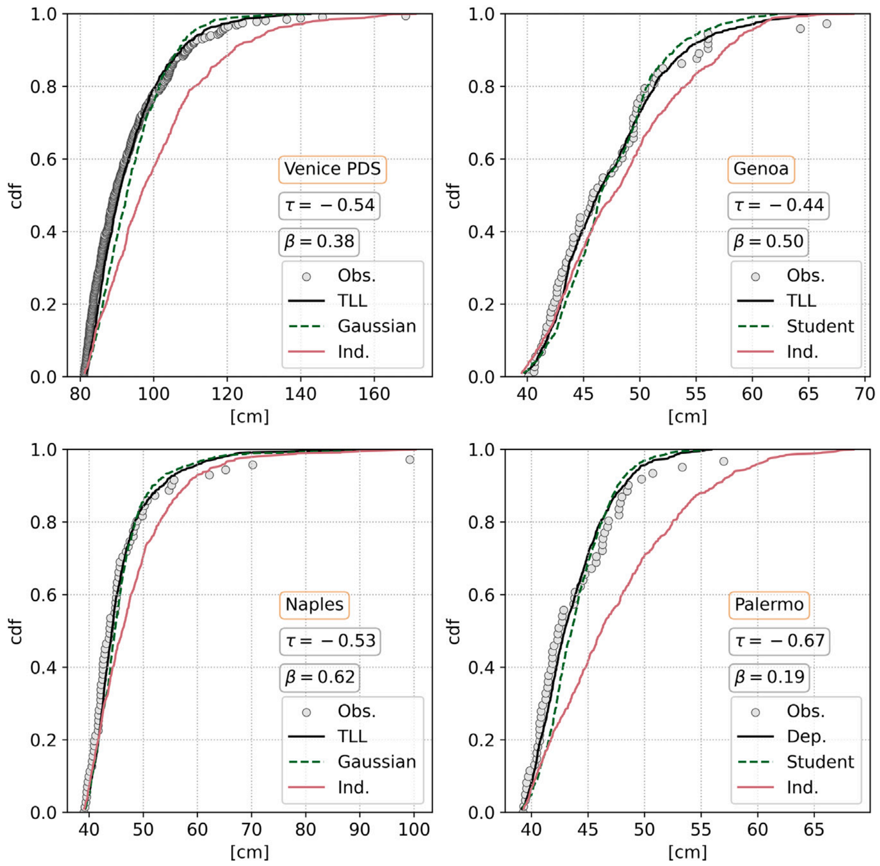

Fig. 5. Comparison between the distributions of extreme sea levels from observations (gray dots), copula-based dependent model (solid black line for TLL and dashed green line for Gaussian/Student copula), and independence copula (red line) to show the additional information brought by the β factor in support to the Kendall's τ on the magnitude of extreme sea level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

not work well when simulating extreme events on the edges of the copula domain. One possibility to overcome such an issue is to consider theoretical margins.

6. Conclusion

We investigated the interaction between tide and surge for extreme conditions of SL in 9 coastal stations along the Adriatic and the Tyrrhenian Seas, all in a micro-tidal and semi-diurnal tidal regime. Our results showed that the pairs of tide and skew surge generating ESLs are negatively dependent, i.e., high/low values of the surge are associated with low/high values of the tide, in all the stations investigated, and that higher values of dependence, measured with Kendall's τ, can be observed in the Adriatic Sea while lower values in the Tyrrhenian Sea, with the exception of Palermo. In general, the effect of explicitly modeling the dependence between tide and surge is an increase in ESLs for higher quantiles and a reduction of ESL variance. Hence, accounting for the observed dependence leads to a better estimate of ESL. Moreover, our results showed the potential of the β factor when used together with a rank-based metric such as Kendall's τ, to better identify how much the tide-surge interaction affects the variability of ESLs and reveal the importance of the relative contribution of tides and surges when estimating ESL.

CRediT authorship contribution statement

Elisa Ragno: Developed the study, Writing – review & editing, Carried out the analyses. **Alessandro Antonini:** Developed the study, Writing – review & editing. **Davide Pasquali:** Developed the study, Writing – review & editing, Collected and processed raw sea level observations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study are publicly available and can be retrieved from the "Rete Mareografica Nazionale" (Italian National Mareographic Network) https://www.mareografico.it/ and from the "Istituto Superiore per la Protezione e la Ricerca Ambientale, ISPRA" https://www.venezia.isprambiente.it/.

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