DOI: https://doi.org/10.53256/COSE_240204

Does Tide–Surge Interaction Occur along the Croatian Coast of the Adriatic Sea?

M. M. Gržić[a,*], N. Ožanić[a] and N. Krvavica[a]

[a]*Faculty of Civil Engineering, University of Rijeka, Radmile Matejčić 3, 51000, Rijeka, Croatia*

[*]*Corresponding author: Marta Marija Gržić, e-mail: mmgrzic@gradri.uniri.hr*

ABSTRACT: Understanding the interaction between storm surges and tidal dynamics is essential for accurately assessing coastal flood risk, particularly in microtidal environments such as the Adriatic Sea. This study evaluates tide–surge interaction (TSI) in three regions of the Adriatic Sea—the northern, middle, and southern Adriatic—using three statistical approaches. The applied methods include: (i) distributing extreme storm surges across tidal ranges, (ii) distributing extreme storm surges relative to high tides, and (iii) assessing the correlation between storm surges and high tides. None of the investigated locations exhibited consistent evidence of tide–surge interaction across all applied methods. Consequently, the results indicate that significant TSI does not occur along the Croatian Adriatic coast, suggesting that storm surges and tidal processes act largely independently in this region.

KEYWORDS: Tide-surge interaction (TSI), Adriatic Sea, Microtidal environment, Extreme sea levels

1 INTRODUCTION

High river discharges, heavy precipitation, extreme storm surges, and severe sea states are key flood drivers that render densely populated coastal areas particularly vulnerable to flooding (Green et al., 2024). While storm surges are primarily driven by atmospheric forcing (Pugh & Woodworth, 2014), their impacts are significantly amplified when they coincide with high tide, resulting in extreme water levels that can threaten coastal infrastructure, communities, and ecosystems. Understanding the interaction between storm surges and tidal dynamics is therefore crucial for accurately assessing coastal flood risk, especially in shallow environments where relatively small changes in water level can have substantial consequences. For this reason, increasing attention has been given to tide–surge interaction (TSI) (Williams et al., 2016). The dominant mechanism underlying TSI involves mutual phase modulation between tides and storm surges (Horsburgh & Wilson, 2007). This interaction is inherently nonlinear and can significantly influence coastal water levels during storm events. Accurately capturing these dynamics is essential for reliable coastal flood forecasting and for the development of effective coastal protection and adaptation strategies.

Numerical modelling of TSI typically involves the combined simulation of tides and storm surges, followed by comparison with scenarios in which tides and surges are modelled separately (Idier et al., 2012). This approach is commonly used to assess the influence of TSI on extreme water levels. In several regions, including the English Channel (Idier et al., 2012), the Bay of Bengal (Antony et al., 2020), the South China Sea (Zhang et al., 2017), the Aveiro Lagoon in Portugal (Pinheiro et al., 2020), and the coast of Taiwan (Liu et al., 2016), the influence of TSI on water levels has been shown to range from a few centimetres to more than one metre. Importantly, the interaction does not always result in higher peak water levels; in some cases, TSI can reduce extreme levels (Antony et al., 2020).

In addition to numerical modelling, several statistical methods have been developed to detect and quantify TSI, including those proposed by Dixon and Tawn (1994), Haigh et al. (2010), Williams et al. (2016), and Arns et al. (2020). The approach of Dixon and Tawn (1994) compares the distribution of all tidal values with the distribution of tides associated with the top 1% of storm surge events using a chi-squared test. The underlying assumption is that, in the absence of statistically significant differences between the two distributions, no significant TSI exists. Conversely, significant distributional differences indicate interaction between tidal and surge

components. Haigh et al. (2010) similarly assessed the distribution of the highest 1% of storm surges relative to tidal phase, where a uniform distribution would be expected in the absence of TSI. Williams et al. (2016) examined the dependence between high tides and skew surges by applying the Kendall rank correlation coefficient and the Anderson–Darling test to compare the distribution of all high tides with those associated with the top 1% of skew surges. Arns et al. (2020) further investigated whether non-tidal residuals depend on astronomical tides during extreme sea-level events, providing a statistical framework for quantifying TSI under conditions most relevant to flood risk assessment.(Arns et al., 2020).
These statistical methods reflect the evolution of TSI research over time. Early studies primarily focused on detecting the presence of TSI (Dixon & Tawn, 1994; Haigh et al., 2010), whereas more recent work has aimed at quantifying its magnitude and relevance for risk assessment (Williams et al., 2016; Arns et al., 2020). While the approach of Dixon and Tawn (1994) is effective for identifying the existence of interaction, it does not allow quantification of its strength. Haigh et al. (2010) highlighted the role of tidal phase, demonstrating that storm surges tend to occur more frequently during specific phases of the tidal cycle. Williams et al. (2016) introduced a more formal dependence framework, combining correlation and goodness-of-fit tests. Arns et al. (2020) advanced this further by quantifying the dependence of non-tidal residuals on tides during extreme events, offering the most risk-relevant assessment, albeit with greater methodological complexity.
TSI has been extensively studied in the North Sea, where strong interactions significantly influence extreme sea levels (Dixon & Tawn, 1994; Horsburgh & Wilson, 2007). In the English Channel, Haigh et al. (2010) found significant TSI at eight out of nine tide gauge stations, with interaction strength increasing eastwards. These findings highlight the importance of accounting for TSI in extreme sea-level and flood risk assessments.
To date, however, no studies have specifically investigated TSI along the Croatian coast of the Adriatic Sea. Given the region's complex coastal morphology, including numerous shallow areas such as bays and estuaries, there is a clear need to assess the potential effects of TSI. Statistical dependence between tides and storm surges may significantly increase—or, in some cases, decrease—coastal flood hazard and risk. Incorporating TSI into flood hazard and risk assessments is therefore essential to improve the accuracy of hazard predictions and to support informed coastal management strategies.
The aim of this study is to investigate the dependence between tides and storm surges in three regions of the Adriatic Sea—the northern, middle, and southern Adriatic—using three different statistical methods to assess the presence and significance of TSI.
The paper is structured as follows. Section 2 describes the study area and its main characteristics, as well as the observational data used. Section 3 outlines the methodology, with Subsection 3.1 addressing data preprocessing and Subsections 3.2–3.4 detailing the applied TSI analyses. Section 4 presents the results (Subsections 4.1–4.3) and discusses the findings (Subsection 4.4). Finally, Section 5 summarises the main conclusions of the study.

2 STUDY AREA AND DATA

The Adriatic Sea is a semi-enclosed basin of the Mediterranean Sea, resembling a narrow channel approximately 800 km long and 200 km wide. It is commonly divided into three main regions: the shallow northern Adriatic, the deeper middle Adriatic, and the deep southern Adriatic (Šepić et al., 2022). Extreme sea levels in the Adriatic are influenced by a combination of processes acting across multiple temporal and spatial scales, with tides, storm surges, and seiches being the dominant contributors (Šepić et al., 2022).
Tides in the Adriatic Sea exhibit both diurnal and semidiurnal characteristics, with tidal ranges increasing from approximately 30 cm in the southern Adriatic to up to 1.2 m in the northern part of the basin (Vilibić et al., 2017; Medvedev et al., 2020). Adriatic tidal dynamics are strongly influenced by the amplification of tidal waves as they propagate from south to north due to the progressive narrowing and shallowing of the basin (Janeković & Kuzmić, 2005).
In a microtidal environment such as the Adriatic Sea, tidal signals are generally weaker than storm surge signals (Međugorac et al., 2016, 2018; Krvavica et al., 2024). Consequently, storm surges represent a key driver of extreme sea-level events in this region. A storm surge is the sea-level response to low-pressure systems, typically accompanied by strong south-easterly Sirocco winds. These winds push seawater towards the northern Adriatic, resulting in the highest surge amplitudes in that region, which can reach up to 1.5 m (Međugorac et al., 2016; Ferrarin et al., 2022). Storm surges, whether occurring independently or in combination with high tides and seiches, significantly contribute to extreme sea levels and coastal flooding in the northern Adriatic, with Venice being among the most

affected locations (Cavaleri et al., 2019; Ferrarin et al., 2022).
The fundamental Adriatic seiche, with a period of approximately 21.2 h (Cerovečki et al., 1997), reach amplitudes exceeding 0.5 m in the northern Adriatic. This oscillation can further amplify sea levels and increase the risk of coastal flooding, particularly in areas with complex coastal morphology, such as along the Croatian coastline (Vilibić et al., 2017; Šepić et al., 2022).
For this study, three locations along the Croatian Adriatic coast were selected to represent the northern Adriatic (Bakar station), middle Adriatic (Prosika station), and southern Adriatic (Ušće station). Figure 1 shows the locations of the selected stations (orange triangles) along the Croatian coast.

Figure 1. Locations of the analysed tide gauge stations along the Croatian Adriatic coast (orange triangles): northern Adriatic (Bakar), middle Adriatic (Prosika), and southern Adriatic (Ušće).

For the northern Adriatic station (Bakar), observational data were obtained from the Bakar tide gauge (Međugorac et al., 2022, 2025). This dataset spans 70 years (1950–2020) with an hourly temporal resolution. For the middle and southern Adriatic stations (Prosika and Ušće), observational data were provided by Croatian Waters and the Croatian Meteorological and Hydrological Service. The hourly tide gauge record for Prosika covers 38 years (1986–2023), while the dataset for Ušće spans 47 years (1977–2023).

3 METHODOLOGY

To investigate whether extreme storm surges coincide with high tides in the eastern Adriatic Sea, the first step was to preprocess the sea-level data in order to extract the tidal and non-tidal residual components, as well as the skew surge.
Three statistical methods were applied to investigate different aspects of the tide–surge interaction (TSI) and to determine whether a statistically significant interaction exists (Dixon & Tawn, 1994; Haigh et al., 2010; Williams et al., 2016).
The null hypothesis underlying all three methods is that storm surges (or skew surges) occur randomly with respect to the tidal phase. Accordingly, these methods assume that any storm surge or skew surge can coincide with any tidal level in the absence of interaction.

3.1 Data preprocessing

The first step in data preprocessing involved separating the hourly total sea-level observations into tidal and non-tidal components. A stationary harmonic analysis was performed using the U-Tide toolbox (Codiga, 2011) on sea-level records from all three stations. The analysis incorporated 62 tidal constituents with frequencies greater than 0.03 cycles per hour (cph). The non-tidal residuals were obtained by subtracting the harmonic tidal predictions from the observed sea-level time series. The skew surge was calculated as the difference between the maximum observed sea level and the predicted high tide within each tidal cycle, regardless of the exact timing of the surge peak relative to the tidal maximum (Haigh et al., 2016).

3.2 Distribution of extreme storm surges across tidal ranges

The first method used to assess tide–surge interaction (TSI), originally proposed by Dixon and Tawn (1994), involves extracting the highest 1% of storm surges and grouping them into tidal bins according to the tidal level at the time each extreme storm surge occurs. The tidal range is divided into five equally spaced bins between low and high astronomical tide (Costa et al., 2023).
If storm surges and tides are independent processes, the distribution of tidal levels associated with extreme storm surges should be identical to the overall distribution of the tidal range. To assess whether the two distributions differ, the chi-squared test (χ^2) is applied. The null hypothesis assumes that both distributions are the same, indicating no interaction between tides and storm surges. At the 95% significance level and with four degrees of freedom (one less than the number of bins), the critical value (χ^2_{crit}) is 9.49. If the calcualted χ^2 value is below χ^2_{crit}, the null hypothesis is not rejected, indicating no statistically significant TSI. Conversely, a χ^2

value greater than 9.49 suggests a statistically significant tide–surge interaction.

3.3 Distribution of storm surges relative to high tide

The second method, adapted from Dixon and Tawn (1994) by Haigh et al. (2010), evaluates the distribution of extreme storm surges relative to the timing of high tide. Storm surges exceeding the 99th percentile are extracted, and the corresponding high tides are identified.

Each extracted storm surge is classified into an hourly bin within a ±6-hour window centred on high tide. Under the null hypothesis of no TSI, the resulting distribution should be uniform, meaning that extreme storm surges are equally likely to occur at any time between −6 h and +6 h relative to high tide.

To test whether the binned storm surge distribution is uniform, the chi-squared test (χ^2) with 12 degrees of freedom is applied at the 95% significance level. χ^2 values below the critical value (χ^2_{crit}) of 21.03 indicate no significant TSI, whereas values exceeding this threshold suggest a statistically significant dependence between storm surges and tidal phase.

3.4 Correlation between skew surges and high tides

While the two previous methods focus on the relationship between extreme storm surges and tides, this method examines the dependence between skew surges and predicted high tides (Williams et al., 2016). An advantage of using skew surge rather than storm surge is that it avoids complications related to tidal timing, as skew surge yields a single value per tidal cycle (Santamaria-Aguilar & Vafeidis, 2018).

Potential storm surge peaks and their times of occurrence, along with high tides, are extracted from the observed sea-level data using an 18-hour moving window. For each high tide, the nearest storm surge peak occurring within ±6 hours is selected to compute the skew surge.

Following Williams et al. (2016), the highest 1% of skew surges are extracted to assess the dependence between extreme skew surges and high tides. The Kendall rank correlation coefficient (τ) is used as the dependence metric. Kendall's τ is a non-parametric measure of monotonic association that is robust to outliers and capable of capturing nonlinear relationships based on data ranks (Li et al., 2012).

If skew surges and high tides are independent, the distribution of high tides associated with the highest 1% of skew surges should be statistically indistinguishable from the distribution of all high tides (Williams et al., 2016). This hypothesis is tested using the Anderson–Darling goodness-of-fit test, with the null hypothesis stating that both samples originate from the same underlying distribution.

4 RESULTS AND DISCUSSION

For all three locations along the Croatian coast of the Adriatic Sea (Fig. 1), tide–surge interaction (TSI) analyses were performed using the three methods described in the previous section. The results are presented separately for each station and subsequently discussed.

4.1 Distribution of extreme storm surges across tidal ranges

4.1.1 Northern Adriatic station (Bakar)

Figure 2 presents histograms of all tidal levels (black) and of tidal levels associated with the extracted extreme storm surge peaks (red dashed) for the Bakar station.

In the central bins (approximately −0.1 to 0.2 m), both distributions exhibit the highest probability densities, indicating that these tidal levels are the most frequent in both datasets. The distribution of all tidal levels shows slightly higher probability densities than the distribution corresponding to storm surge peaks, suggesting that average tidal levels are common in both datasets, but even more prevalent in the overall tidal record.

In contrast, in the outer bins, tidal levels associated with storm surge peaks display higher probability densities, indicating that very low or very high tidal levels more frequently coincide with extreme storm surge events. This comparison illustrates whether tidal levels during storm surge peaks are randomly distributed across the tidal cycle or preferentially occur at specific tidal phases.

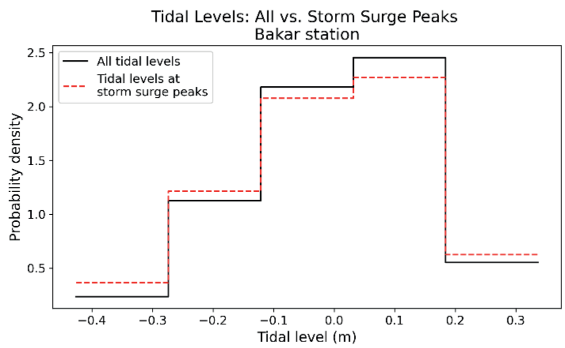

Figure 2. Histograms of tidal levels at the Bakar station for all tidal levels (black) and for tidal levels corresponding to the extracted highest 1% of storm surges (red dashed).

The difference in probability density between the distribution of tidal levels during storm surge peaks and the expected distribution based on all tidal levels at the Bakar station is shown in Fig. 3. Distinct deviation peaks around −0.3 m and 0.25 m indicate that tidal levels during storm surge peaks occur more frequently than would be expected from the general tidal distribution. The oscillatory nature of the deviation suggests that storm surge peaks are more often associated with both lower-than-average and higher-than-average tidal levels, while being less likely to occur when the tide is near its mean value.

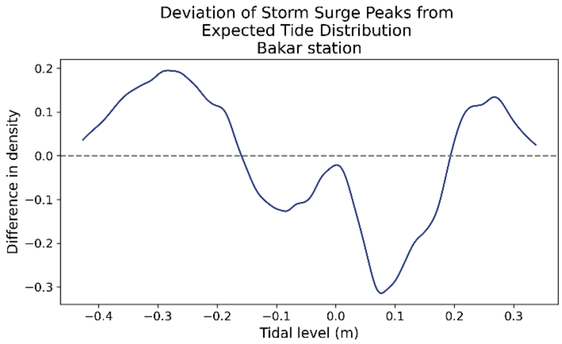

Figure 3. Deviation of the highest 1% of storm surges from the expected tidal distribution at the Bakar station.

For the Bakar station, the chi-squared test yields a χ^2 value of 100.41 at the 95% significance level. As this value greatly exceeds the critical value χ^2_{crit}, the null hypothesis is rejected, indicating a statistically significant difference between the distributions and confirming a strong presence of tide–surge interaction.

4.1.2 Middle Adriatic station (Prosika)

Histograms for the Prosika station indicate that the highest probability densities for both datasets occur within the two central tidal ranges, with a slight shift toward lower tidal levels (Fig. 4). Although the overall shapes of the two distributions are similar, notable differences are observed across most tidal ranges, particularly in the second and third bins. These differences suggest the potential presence of tide–surge interaction (TSI).

The deviations for the Prosika station are shown in Fig. 5. A pronounced positive deviation peak is observed around −0.1 m, indicating that storm surge peaks are considerably more likely to occur at this lower tidal level. This pattern suggests a preference for storm surge peaks to coincide with slightly lower-than-average tidal conditions, rather than with mean or extreme tides.

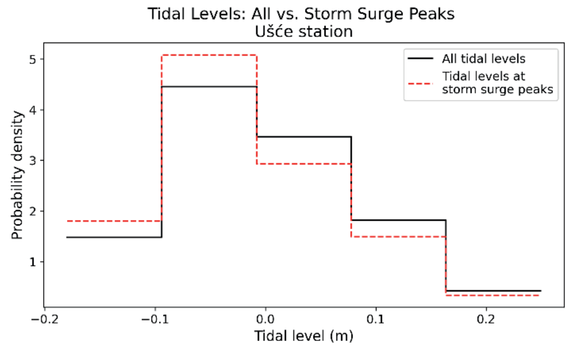

Figure 4. Histograms of tidal levels at the Prosika station for all tidal levels (black) and for tidal levels corresponding to the extracted highest 1% of storm surges (red dashed).

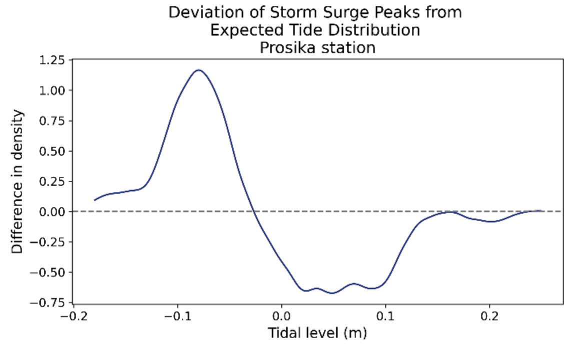

Figure 5. Deviation of the highest 1% of storm surges from the expected tidal distribution at the Prosika station.

For Prosika, the chi-squared test yields a χ^2 value of 79.30 at the 95% significance level. As for the Bakar station, this value greatly exceeds the critical value χ^2_{crit}, leading to a strong rejection of the null hypothesis of no TSI and indicating a substantial tide–surge interaction.

4.1.3 Southern Adriatic (Ušće)

Figure 6 presents histograms for the Ušće station. Both datasets exhibit their highest probability densities around average tidal levels, indicating that these conditions are the most frequent. In contrast, the lowest and highest tidal ranges display very low probability densities, confirming that extreme tidal levels are rare in both datasets. The largest differences between the two distributions occur in the central tidal ranges, whereas the outer ranges are nearly identical.

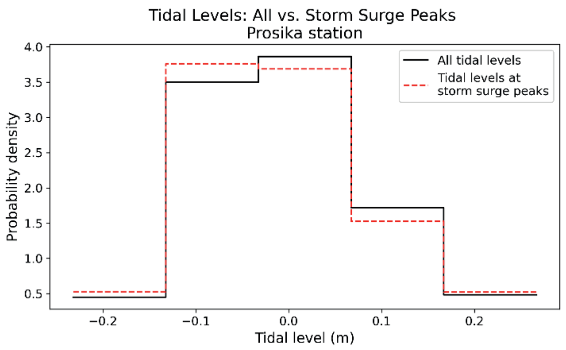

Figure 6. Histograms of tidal levels at the Ušće station for all tidal levels (black) and for tidal levels corresponding to the extracted highest 1% of storm surges (red dashed).

At the Ušće station, a deviation pattern similar to that observed at Prosika is evident in Fig. 7. The highest positive deviations occur around a tidal level of −0.1 m, after which the deviations become negative and decrease in magnitude. This pattern indicates that storm surge peaks tend to coincide with slightly lower-than-average tidal levels rather than with mean or extreme tides.

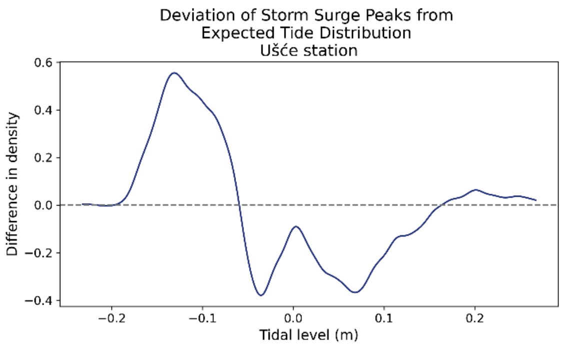

Figure 7. Deviation of the highest 1% of storm surges from the expected tidal distribution at the Ušće station.

For Ušće, the chi-squared test yields a χ^2 value of 18.44 at the 95% significance level. Since $\chi^2 > \chi^2_{crit}$, the null hypothesis is rejected, indicating a statistically significant difference between the distributions and confirming the presence of a notable tide–surge interaction.

4.2 Distribution of storm surges relative to high tide

4.2.1 Northern Adriatic (Bakar)

Figure 8 shows the distribution of storm surges relative to high tide at the Bakar station. The observed distribution appears relatively uniform across the tidal cycle, with only minor deviations from the expected uniform distribution. The absence of pronounced peaks or troughs in the histogram indicates minimal tide–surge interaction (TSI) at this location.

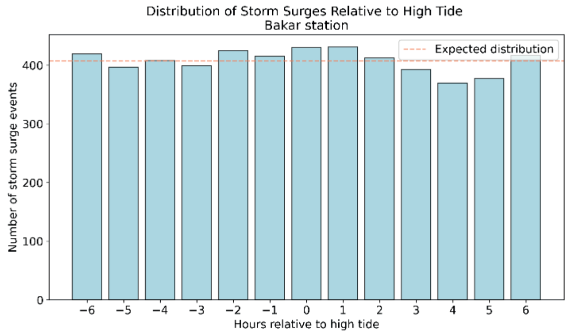

Figure 8. Distribution of the highest 1% of storm surges relative to high tide compared with the expected uniform distribution at the Bakar station.

To support the visual interpretation of Fig. 8, a chi-squared test was performed using a critical value of $\chi^2_{crit} = 21.03$ at the 95% significance level. The resulting χ^2 value of 10.79 is below χ^2_{crit}, confirming that no statistically significant TSI is present at Bakar.

4.2.2 Middle Adriatic (Prosika)

The distribution of storm surges at the Prosika station differs substantially from that observed at Bakar (Fig. 9). A higher frequency of storm surge events occurs five to six hours before high tide, as well as between three and six hours after high tide. Conversely, a noticeable reduction in storm surge occurrences is evident from three hours before to one hour after high tide. This pattern suggests that storm surges at Prosika are less likely to occur shortly before high tide and are more likely to occur toward the beginning and end of the tidal cycle.

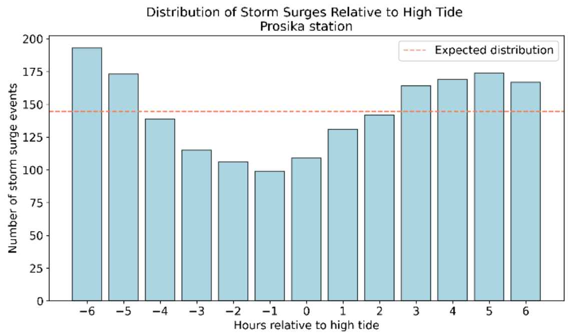

Figure 9. Distribution of the highest 1% of storm surges relative to high tide compared with the expected uniform distribution at the Prosika station.

The chi-squared test confirms the visual interpretation, yielding a χ^2 value of 78.95 at the 95% significance level. As this value is well above χ^2_{crit}, the null hypothesis of no TSI is strongly rejected, indicating a substantial tide–surge interaction at Prosika.

4.2.3 Southern Adriatic (Ušće)

Similar to Prosika, the distribution of storm surges at the Ušće station shows clear deviations from the expected uniform distribution (Fig. 10). As at Prosika, storm surges are less likely to occur shortly before high tide and more likely to occur toward the beginning and end of the tidal cycle.

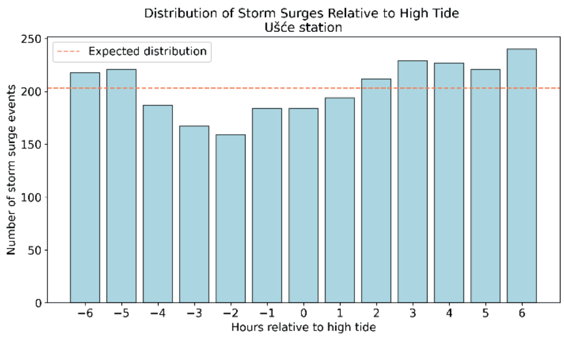

Figure 10. Distribution of the highest 1% of storm surges relative to high tide compared with the expected uniform distribution at the Ušće station.

The chi-squared test yields a χ^2 value of 38.68, which exceeds χ^2_{crit}, indicating that the distribution of storm surges differs significantly from a uniform distribution. Therefore, a statistically significant tide–surge interaction is present at Ušće.

4.3 Correlation between skew surges and high tides

4.3.1 Northern Adriatic (Bakar)

The relationship between the highest 1% of skew surges and the corresponding astronomical high tides at the Bakar station is shown in Fig. 11, together with a visual trend line. Kendall's τ for this station is −0.08 and is not statistically significant ($p > 0.05$), indicating no measurable dependence between skew surges and high tides.

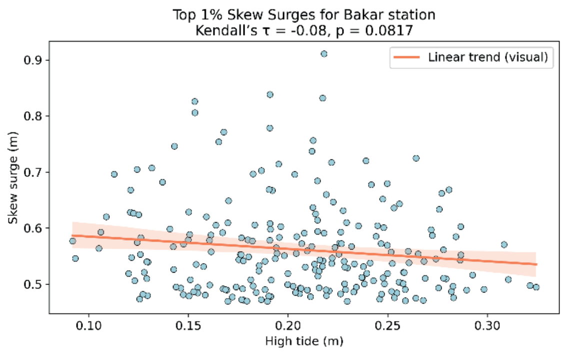

Figure 11. Scatter plot of the highest 1% of skew surges and corresponding high tides, including a visual trend line and Kendall's τ, at the Bakar station.

This lack of correlation suggests that skew surges at Bakar occur independently of astronomical high tides.

Figure 12 presents probability density functions (PDFs) of all high tides and of high tides associated with 99th-percentile skew surges, overlaid with a histogram of high tides during extreme skew surge events at Bakar. Both distributions exhibit a similar bell-shaped form, indicating that the distribution of high tides during extreme skew surges closely resembles the overall high-tide distribution. The peak of the black dashed curve is slightly shifted toward higher values compared with the orange curve, suggesting that extreme skew surges at Bakar tend to occur during slightly higher-than-average high tides.

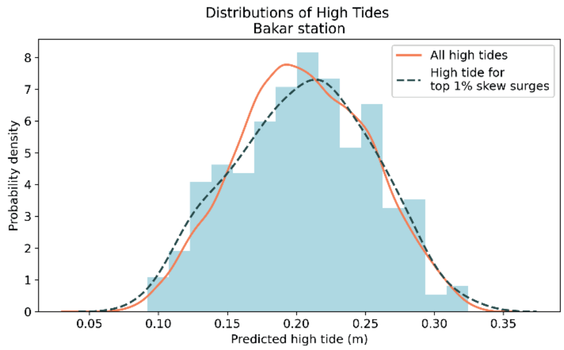

Figure 12. Probability density functions of all high tides and of high tides occurring during extreme skew surges, together with a histogram of high tides associated with skew surges at the Bakar station.

If skew surges and high tides are independent, high tides associated with extreme skew surges should follow the same distribution as all high tides (Williams et al., 2016). The Anderson–Darling test was therefore applied to compare the two distributions. The test failed to reject the null hypothesis ($p > 0.05$), indicating no statistically significant difference between them. Consequently, no significant tide–surge interaction is detected at the Bakar station based on this method.

4.3.2 Middle Adriatic (Prosika)

The correlation between the highest 1% of skew surges and the corresponding high tides at the Prosika station is shown in Fig. 13, together with a visual trend line. Kendall's τ for this location is −0.05 and is not statistically significant ($p > 0.05$). The absence of a statistically significant correlation indicates no dependency between skew surges and high tides and, therefore, no evidence of tide–surge interaction (TSI) at this station.

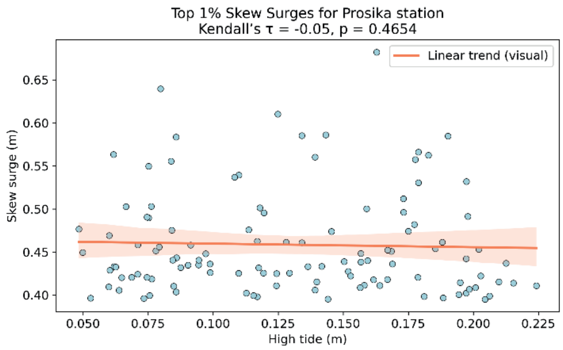

Figure 13. Scatter plot of the highest 1% of skew surges and corresponding high tides, together with a visual trend line and Kendall's τ, at the Prosika station.

Figure 14 presents the probability density functions (PDFs) and histogram for the Prosika station. The dashed black curve (high tides associated with extreme skew surges) peaks at lower tidal levels (≈0.07 m), whereas the orange curve (all high tides) peaks at slightly higher levels (≈0.10 m). This shift suggests that extreme skew surges at Prosika tend to occur more frequently during lower-than-average high tides.

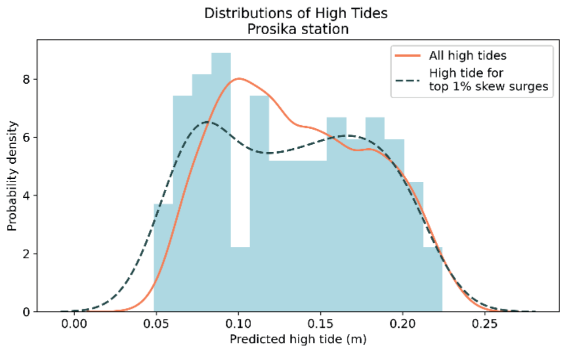

Figure 14. Probability density functions (PDFs) of all high tides and of high tides occurring during extreme skew surges, together with a histogram of high tides associated with skew surges at the Prosika station.

The Anderson–Darling test was applied to compare the distribution of all high tides with that of high tides associated with the highest 1% of skew surges at the Prosika station. The test statistic was 1.9504, slightly below the critical value of 1.9610 at the 95% significance level, with a p-value of 0.0510. Consequently, the null hypothesis of no difference between the distributions is not rejected.
This result indicates that there is no statistically significant difference between the two distributions, supporting the conclusion derived from Kendall's τ that no significant TSI is present at this station.

4.3.3 Southern Adriatic (Ušće)

The Ušće station exhibits the lowest correlation coefficient among the three locations, with a Kendall's τ value of −0.01 (Fig. 15). As for the other stations, this correlation is not statistically significant, indicating no meaningful relationship between skew surges and high tides and, consequently, no evidence of TSI at this location.

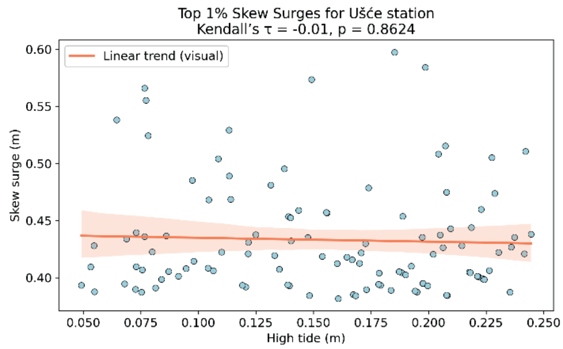

Figure 15. Scatter plot of the highest 1% of skew surges and corresponding high tides, together with a visual trend line and Kendall's τ, at the Ušće station.

The differences between the distributions shown in Fig. 16 were assessed using the Anderson–Darling test. As expected, no statistically significant difference was identified. The test statistic was −0.5716, which is well below the critical value of 1.9610 at the 95% significance level, confirming the absence of significant TSI at the Ušće station.

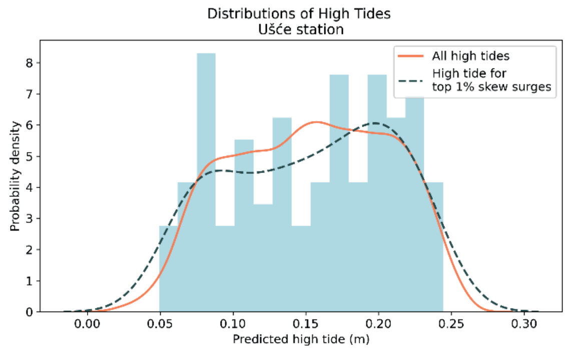

Figure 16. Probability density functions (PDFs) of all high tides and of high tides occurring during extreme skew surges, together with a histogram of high tides associated with skew surges at the Ušće station.

4.4 Discussion

The analysis of tide–surge interaction (TSI) at the three tide gauge stations along the Croatian Adriatic coast produced method-dependent results, with no station showing consistent evidence of TSI across all applied approaches.

At the northern Adriatic station, Bakar, TSI was identified only by the method based on the distribution of extreme storm surges across tidal ranges (Dixon & Tawn, 1994). In contrast, the second method (Haigh et al., 2010) , which evaluates whether extreme storm surges preferentially occur during high tides, and the third method (Williams et al., 2016), which examines the correlation and distributional similarity between skew surges and high tides, both failed to detect statistically significant TSI. This lack of agreement among methods supports the conclusion that TSI at Bakar is weak or not statistically significant.
At the middle Adriatic station, Prosika, both the first and second methods indicated statistically significant TSI, suggesting that extreme storm surges tend to occur under specific tidal conditions. However, the third method revealed no significant correlation between skew surges and high tides, and the Anderson–Darling test statistic (1.9504) did not exceed the 5% critical value (1.9610), yielding a p-value of 0.0510. Although close to the significance threshold, this result does not justify rejection of the null hypothesis. This inconsistency introduces uncertainty: while two methods suggest the presence of TSI, the absence of confirmation from the third method renders the overall result inconclusive.
A similar pattern was observed at the southern Adriatic station, Ušće. Again, the first two methods indicated significant TSI, whereas the third method did not. The correlation between skew surges and high tides was negligible ($\tau = -0.01$), and no statistically significant difference was found between the relevant tidal distributions.
The systematic non-detection of TSI by the third method, despite contrasting results from the other two approaches, may be attributed to its stricter statistical requirements and reduced sensitivity when applied to limited samples of extreme events. In particular, the relatively small number of extreme skew surges may reduce the statistical power of the Anderson–Darling test to identify meaningful deviations. Consequently, the failure of the third method to detect TSI should be interpreted with caution, especially when its results contradict those of multiple independent methods.

CONCLUSIONS

To examine whether extreme storm surges tend to coincide with high tides along the Croatian Adriatic coast, three complementary statistical methods were applied at the Bakar, Prosika, and Ušće tide gauge stations, representing the northern, middle, and southern Adriatic, respectively.
While the first two methods provided evidence of tide–surge interaction (TSI) at the middle and southern Adriatic stations, the third method consistently failed to confirm any statistically significant interaction. The differing outcomes among the three methods can be attributed to the fact that they capture distinct aspects of TSI.
The first method, based on histogram and deviation analyses, offers a direct visual and statistical comparison between tidal levels at storm surge peaks and the overall tidal distribution, making it sensitive to preferential occurrence at specific tidal levels. The second method, which examines the timing of storm surges relative to high tides, focuses on the distribution of surge events across the tidal cycle and is better suited to identify systematic clustering around particular tidal phases. In contrast, the skew surge–high tide correlation approach tests for statistical dependence between two variables, assessing whether extreme surges preferentially coincide with high tides; however, it may overlook interactions occurring at lower or intermediate tidal levels. Consequently, discrepancies among the three methods arise because they quantify different manifestations of TSI—namely, distributional differences, phase preferences, or direct statistical dependence.
Given the lack of consistent agreement across methods and the stringent criteria of the skew surge–based approach, the overall results suggest that storm surges and tides along the Croatian Adriatic coast generally occur independently, with no conclusive evidence of statistically significant tide–surge interaction.
Future research will focus on the application of non-stationary harmonic analysis techniques (e.g., NS_Tide) to explicitly identify potential interactions between storm surges and tides, as well as the modulation of tidal constituents during extreme surge events. Such analyses may provide additional insight into compound sea-level dynamics that can substantially influence coastal flooding.

ACKNOWLEDGEMENTS

This work was supported by the Croatian Science Foundation under the project “Compound Flooding in Coastal Croatia under Present and Future Climate” (4SeaFlood, project number IP-2022-10-7598), and by the University of Rijeka through projects uniri-iskusni-tehnic-23-83 and uniri-iskusni-tehnic-23-74. The authors gratefully acknowledge Croatian Waters and the Croatian Meteorological and Hydrological Service for providing the observational data.

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