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Analysis of Monthly Recorded Climate Extreme Events and Their Implications on the Spanish Mediterranean Coast

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Abstract: Due to climate change, hydroclimatic extremes are becoming more frequent and intense and their characterization and analysis is essential for climate modelling. One of the regions that will be most affected by these extremes is the Mediterranean coast of Spain. Therefore, this paper analyses the significant wave height (Hs), peak wave period (Tp) and sea level (SL) extremes and their correlation along the Spanish Mediterranean coast. After conducting this analysis, it is finally concluded that and adjustment of the extreme long-term distribution of Tp is urgently needed to create accurate models and projections, which must be considered in combination with the intense extremes happening in the Levantine basin when modelling this area and designing new projects.

Keywords: extremes; wave height; sea level; wave period; Mediterranean coast; Spain; modelling

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1. Introduction

Climate change is causing temperatures to rise, which in turn is leading to rising sea levels and hydroclimatic extreme events, among others. In this context, it is crucial to analyse and properly model these events and their impacts on society, infrastructure and ecosystems.

One of the main hotspots of climate change is the Iberian Peninsula and its Mediterranean coast due to its location and orography [1]. Villeta et al., 2018 [2], proved an increase in the number of annual days with extreme minimum and maximum temperatures in the north of Spain. Quereda et al., 2018 [3] showed an increase of temperatures in Valencia. Lorenzo et al., 2021 [4] stated that in the whole Iberian Peninsula heatwaves will have a higher heat excess and heatwave days will become more intense in the near future. Kelebek et al., 2021 [5] highlighted that the aridity index over the Mediterranean has increased since the 1970s. As noted above, this increase of temperatures is provoking sea level rise (SLR) and hydroclimatic extreme events. Therefore, there are many scientific papers that study the consequences that climate change will have in Spain. In this section, some of the studies carried out in Spain, specifically focused on hydroclimatic extreme events, are presented.

In 2008, Lionello et al. [6] simulated the changes of wave climate for future scenarios and saw a slightly downward trend in wave height. The same year, Kundzewicz et al. [7] studied the impacts of hydroclimatic extreme events on different economic sectors. In 2016, Rueda et al. [8] developed a methodology to characterize extreme wave heights by defining weather types of the synoptic circulation conditions, and Lin Ye et al. [9] developed a statistical model of extreme events that applied to the Catalan Coast. In 2016 also, Vousdoukas et al. [10] projected extreme storm surge levels along Europe and concluded a negative trend in the Bay of Biscay and no changes in the Mediterranean Sea. In 2018, Dental et al. [11] discussed the problems of using model data to evaluate extreme waves and two years later, they developed a methodology to integrate model data with buoy data. Wolff et al. [12] also developed a database for assessing the impact of extreme

waves and SLR in the Mediterranean in 2018, and Sayol and Marcos [13] achieved the same for the Ebro Delta.

In 2020, Abdalazeez et al. [14] stated that gentle beaches acted like a "low-pass filter" for extreme wave heights and de Lalouvière et al. [15] pointed out the necessity of maintaining reef health to assure wave energy dissipation. In the last few years, there have also been many studies focused on SLR and extreme flooding, as it is one of the greatest challenges for today's society [16]. Eguibar et al. studied these flood hazards in Oliva, Valencia [17]; Hernandez-Mora et al. [18] in Tossa del Mar, Catalonia; Lopez-Doriga and Jimenez [19] in the Ebro Delta; Luque et al. [20] in the Balearic islands; and Carmen Llasat [21] studied the evolution of these phenomena in the Mediterranean region.

In 2021, de Alfonso et al. [22] studied the effects of the extreme storm Gloria in Spain. Amarouche, and Akpinar [23], and De Leo et al. [24] characterized extreme wave events in the Mediterranean Sea and pointed out an increasing trend. In 2022, Hsu et al. [25] studied the effect of extreme waves in vertical breakwaters stability, and Iglesias et al. [26] modelled climate change projections in estuarine regions.

Although, as has been seen above, there are a large number of climate studies along the Spanish coast, the Levante area is one of the least studied areas. The Levantine basin is an enclosed basin affected by regional wave and wind patterns that are different from the global patterns. Despite this condition, most of the studies of the Levantine basin focus on very specific points, such as the Ebro Delta or the Catalan Maresme, leaving many areas without climatic studies [1,27,28]. Figure 1 presents a colour scale to illustrate the relative number of climate studies that have been carried out on each Spanish coast.



Figure 1. Number of studies in Spain. Taken from [1].

This article seeks to address this problem and attempts to tackle this lack of studies in the Levantine basin, focusing on the study and analysis of extreme storms along the Mediterranean coast of Spain. This analysis of extreme hydroclimatic events will help to fill the gap of studies in the Levantine basin and to characterize this part of the Spanish coast. Studying extreme storms is essential to avoid economic and human loss and structural damage. Particularly in this area, where major storms have already caused such things.

The structure of the paper is as follows: Section 2 describes the methodology. Section 3 shows the results obtained and the analysis carried out. Section 4 presents the discussion of the results, and Section 5 highlights the main conclusions and suggests new research directions.

2. Materials and Methods

For this study, all the monthly maximums of Hs, Tp, and sea level (SL) along the Mediterranean Sea of the network of Spanish ports have been collected and analysed. The data records range from the operating start of buoys and tide-gauges to the present. These records have also been compared to the annual reports and summaries of Spanish ports.

All the data were taken from the Spanish ports' website [29]. Data have been collected from the available buoys and tide gauges along the Spanish Mediterranean coast. Of all the available buoys and tide gauges, all those who met the following criteria were chosen for the analysis:

1. The buoys must have sufficiently long records, at least 10 years (without large data gaps). This criterion was chosen because in order to draw conclusions regarding extreme events, a data series of at least 10 years is necessary.
2. The buoys must be located in deep water, sufficiently far from the coast so that they are not affected by refraction, diffraction and shoaling phenomena that could alter the final results.

It should be noted that the Spanish port buoys are composed of scalar buoys of the Waverider (Datawell) type and directional buoys of the Triaxys™ (Axys) type.

Figure 2 shows all the buoys and tide gauges chosen for the study, and the buoys and tide gauges used are also listed in Tables 1 and 2, respectively.



Figure 2. Buoys and tide gauges used in the study.

The study was conducted in three different blocks: first, the values of Hs and Tp were studied; then the SL variable; and finally, the correlation between the extremes of all the variables (Hs, Tp and SL).

To analyse and construct the data of Hs and Tp, the first step was to choose the corresponding buoy of the section of oceanography of the Spanish ports' website. Once the buoy was selected, the report was downloaded and the option "monthly maximums" was selected to download the data [30]. All the data were plotted and studied statistically. In addition, the parameters of α, β, γ and λ; Hs and Tp for 20, 50 and 100 years and their evolution in time were studied in each buoy.

Table 1. List of buoys used in the study.

Buoy	Longitude	Latitude	Depth	Records
1. Gulf of Cadiz	6.96° W	36.49° N	466 m	1996–2022
2. Alborán	5.03° W	36.27° N	585 m	1997–2006
3. Cabo de Gata	2.34° W	36.57° N	545 m	1998–2022
4. Cabo de Palos	0.31° W	37.65° N	242 m	2006–2022
5. Valencia	0.20° E	39.51° N	349 m	2005–2022
6. Mahon	4.42° E	39.71° N	310 m	1993–2022
7. Tarragona	1.47° E	40.69° N	685 m	2004–2022
8. Begur	3.65° E	41.90° N	1355 m	2001–2022

Table 2. List of tide gauges used in the study.

Tide Gauge	Longitude	Latitude	Records
1. Tarifa	5.60° W	36.01° N	2009–2020
2. Algeciras	5.40° W	36.18° N	2009–2020
3. Almeria	2.48° W	36.83° N	2006–2020
4. Valencia	0.31° W	39.44° N	1993–2020
5. Mahon	4.27° E	39.89° N	2009–2020
6. Sagunto	0.21° W	39.63° N	2007–2020
7. Tarragona	1.21° E	41.08° N	2011–2020
8. Barcelona	2.17° E	41.34° N	1993–2020

It is important to examine the evolution of α, β, γ and λ because they are the statistical parameters that characterize the extreme long-term distribution. α is the Hs threshold, β is the scale parameter and γ is the shape coefficient. α, β and γ are the three parameters that characterize Weibull distribution (Equation (1))

$$F_w(H_s < x) = 1 - \exp\left(-\left(\frac{x-\alpha}{\beta}\right)^{\gamma}\right) \quad (1)$$

λ is the number of the average number of storms occurring in a year and it is normally used in the POT (Peaks Over the Threshold) distribution (Equation (2)).

$$H_{s|Tr|} = \alpha + \beta\left[-\ln\frac{1}{\lambda Tr}\right]^{1/\gamma} \quad (2)$$

Tp for 20, 50 and 100 years are the Tp expected in 20, 50 and 100 years, respectively. These values are obtained applying the POT distribution (Equation (2)) for the 20, 50 and 100 years return period. Once the Hs is obtained, Equation (3) is applied

$$Tp = aHs^b \quad (3)$$

The parameters a, b, α, β, γ and λ are obtained for each buoy from "Puertos del Estado" reports [31].

To analyse and construct the data of SL, the procedure followed was very similar to the method explained above but instead of taking the buoy records, tide gauge records were downloaded [32].

Finally, a statistical study was carried out to analyse the correlation of the hydroclimatic extremes. In this part of the study, the methodology was different. First, the monthly extremes of SL and the day and hour when the event happened were collected. Then, a

search for the wave occurring at that hour was carried out and the values were plotted. Therefore, the main variable in the correlation analysis conducted was the SL, and the secondary value was the wave height.

3. Results

This section is divided into four subsections. Section 3.1 is the study of Hs and Tp, in which the evolution of the parameters Hs and Tp of each buoy is presented. Section 3.2 is the study of extreme statistical parameters. Section 3.3 is the study of SL, similar to Section 3.1, but analysing the SL variable. Section 3.4 is the correlation of hydroclimatic extremes, in which the correlation of the extremes of Hs, Tp and SL is studied.

3.1. Study of Hs and Tp Monthly Extremes

The evolution of monthly Hs extreme records is presented in Figures 3–10. The Y-axis is the Hs in m and X-axis the time. All the X-axes of this section have been unified to facilitate the comparison of the different spots. All the figures presented have an X-axis that goes from January 2000 to March 2022 even if there were more records or less than this year frame. As mentioned above, it was decided to unify all graphs in order to facilitate the interpretation and comparison of the results.

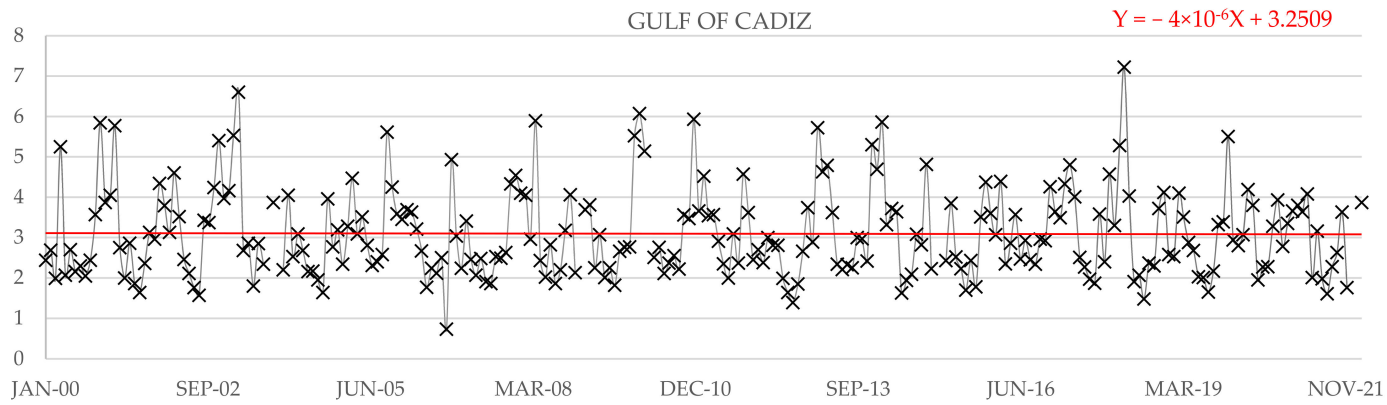


Figure 3. Evolution of Hs maxima in the Gulf of Cadiz.

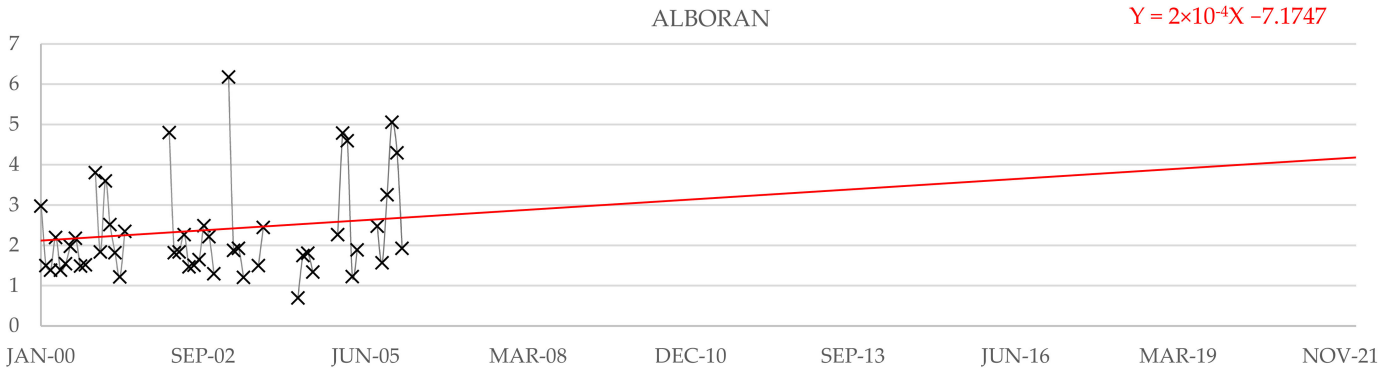


Figure 4. Evolution of Hs maxima in Alboran.

Each graph also shows the trend line following the maxima of Hs and its analytical expression (in the colour red). This was carried out by means of a linear adjustment because it was considered to give the most visual and tangible image of the trend followed by the extremes. This will facilitate the analysis of the results and the reaching of the conclusions presented in Sections 4 and 5.

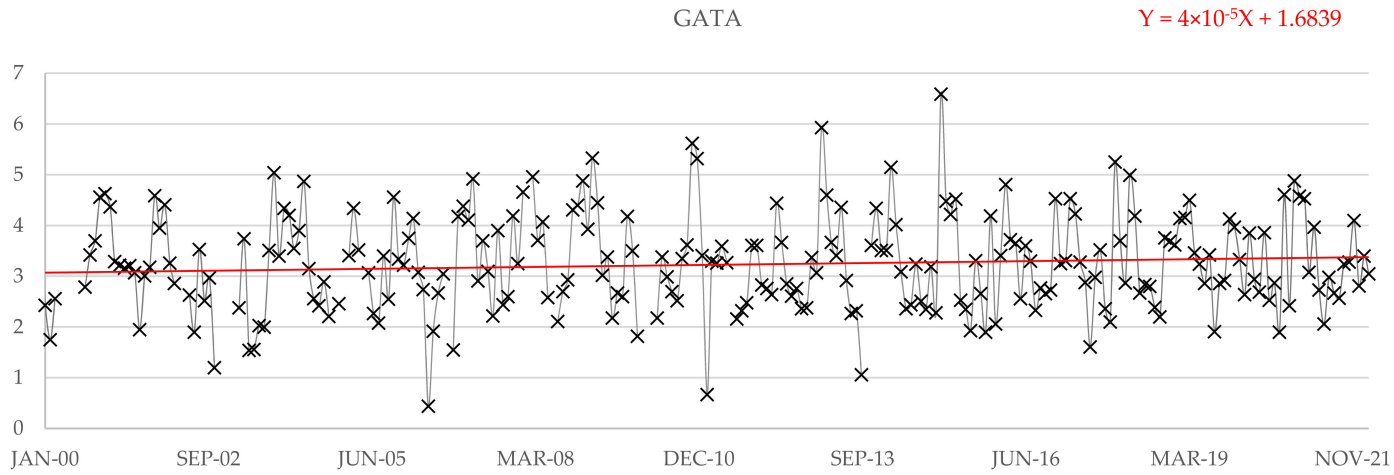


Figure 5. Evolution of Hs maxima in Cabo de Gata.

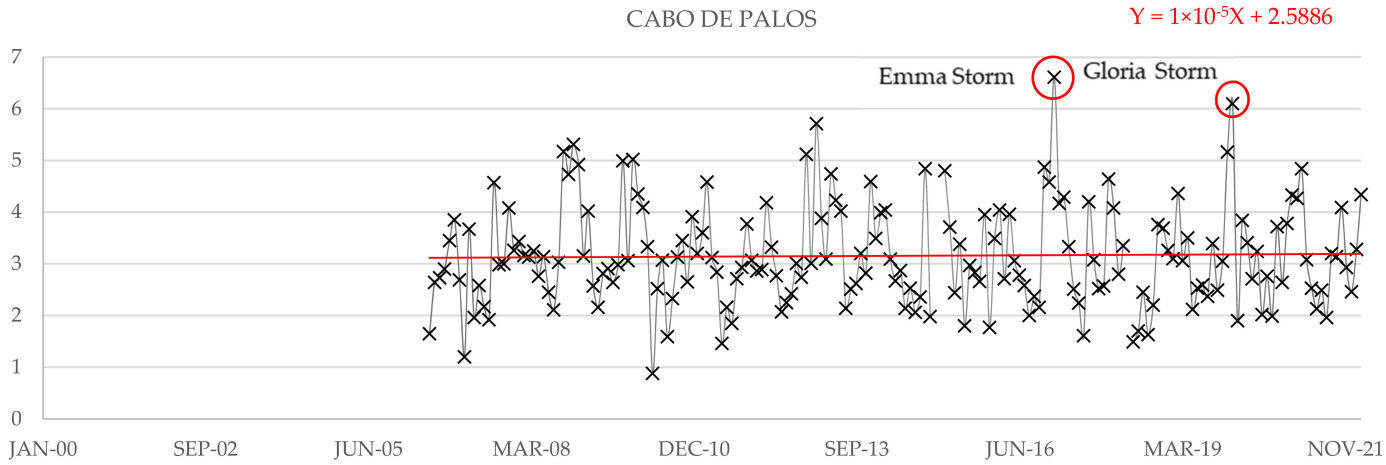


Figure 6. Evolution of Hs maxima in Cabo de Palos.

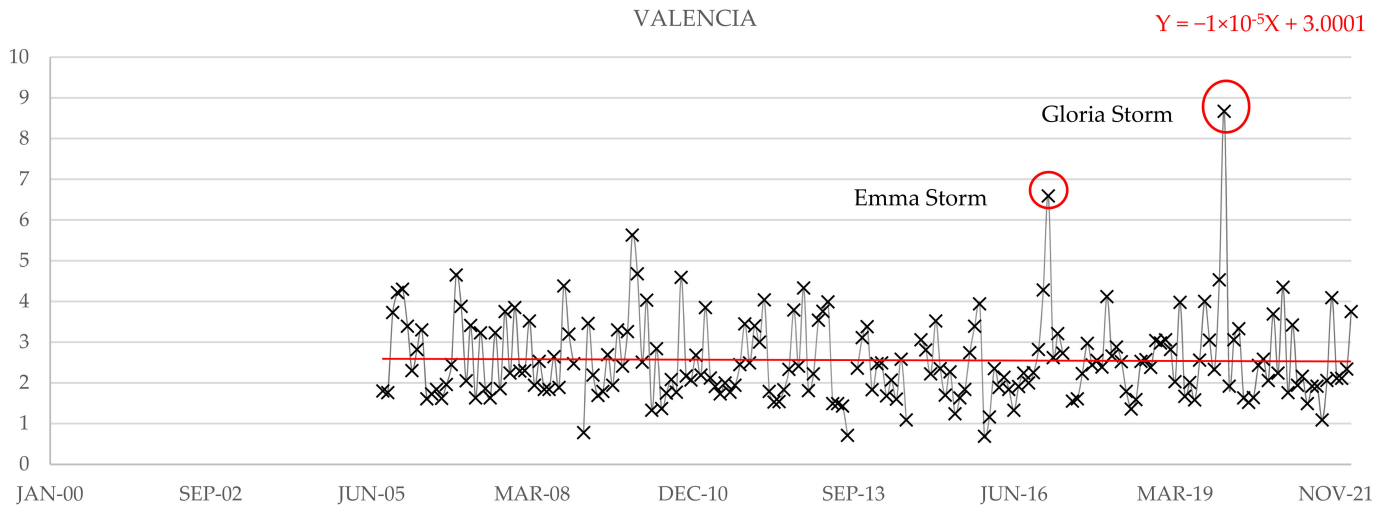


Figure 7. Evolution of Hs maxima in Valencia.

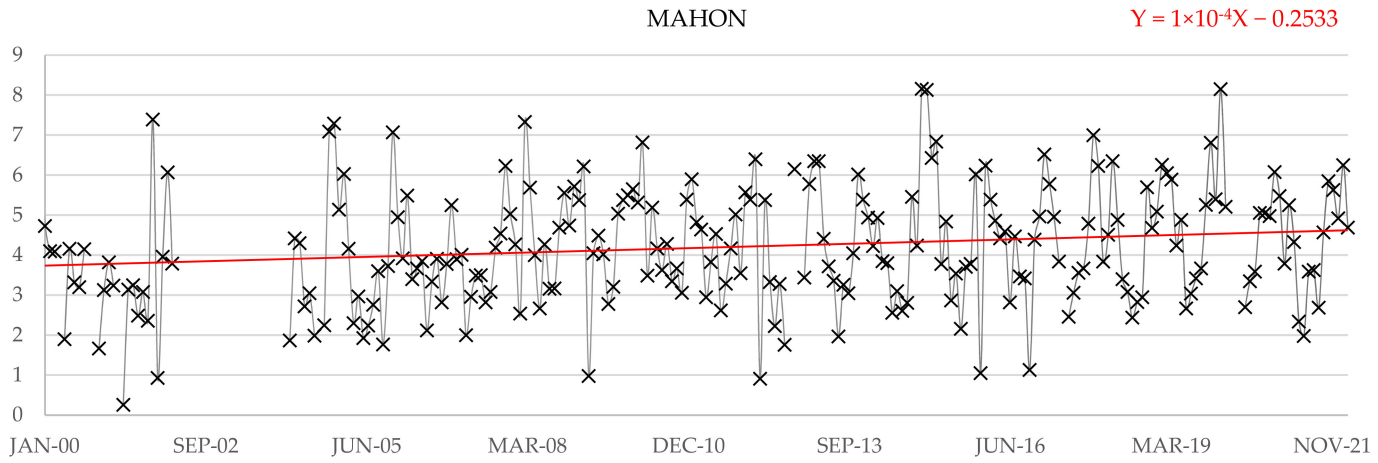


Figure 8. Evolution of Hs maxima in Mahon.

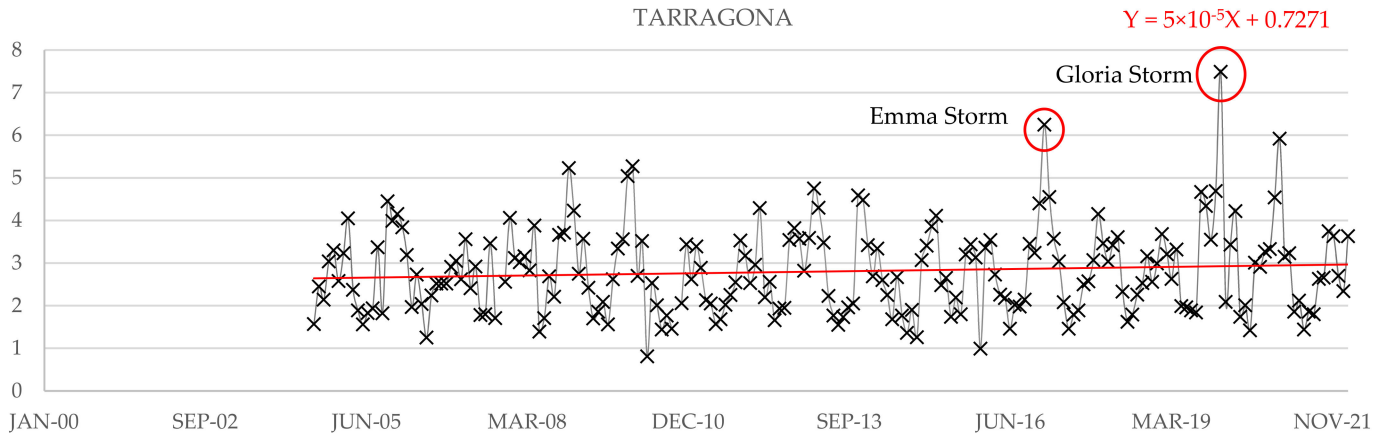


Figure 9. Evolution of Hs maxima in Tarragona.

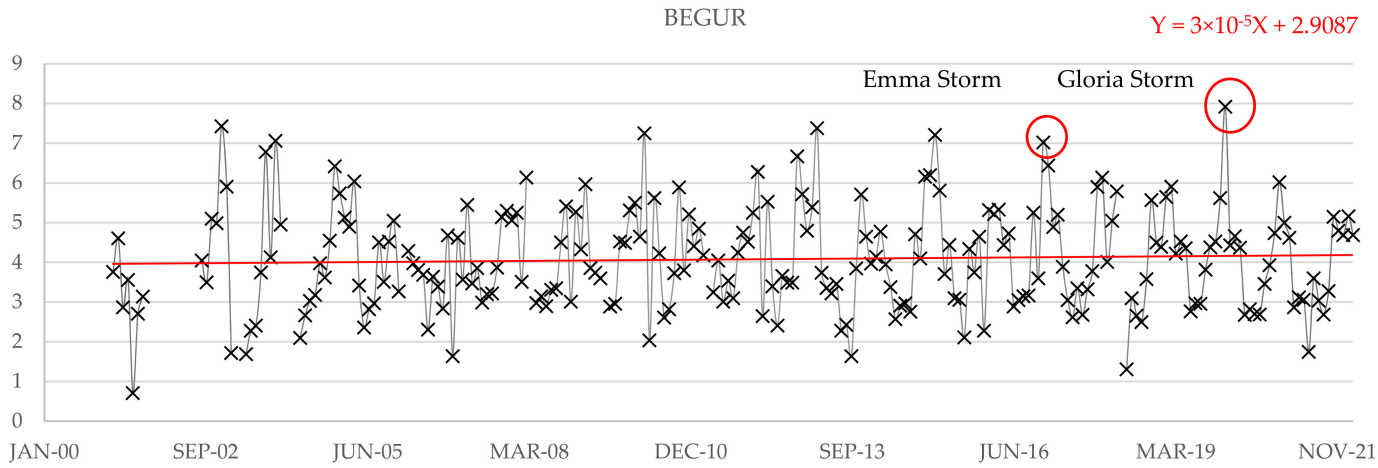


Figure 10. Evolution of Hs maxima in Begur.

The evolution of monthly Tp extremes is presented in Figures 11–18. As was done with Hs, the trend line is presented in the graphs and the adjustment performed is linear due to the same reason (colour red). The Y-axis is the Tp in s, and the X-axis the time. The X-axis of the graphs has also been unified and all X-axes of Figures 11–18 range from January 2000 to March 2022.

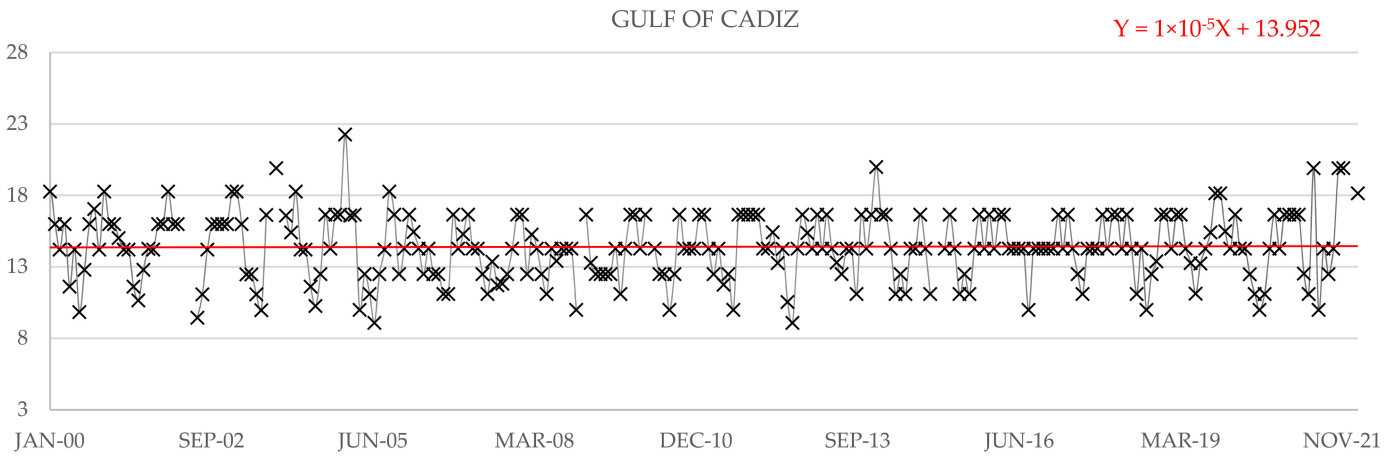


Figure 11. Evolution of Tp maxima in the Gulf of Cadiz.

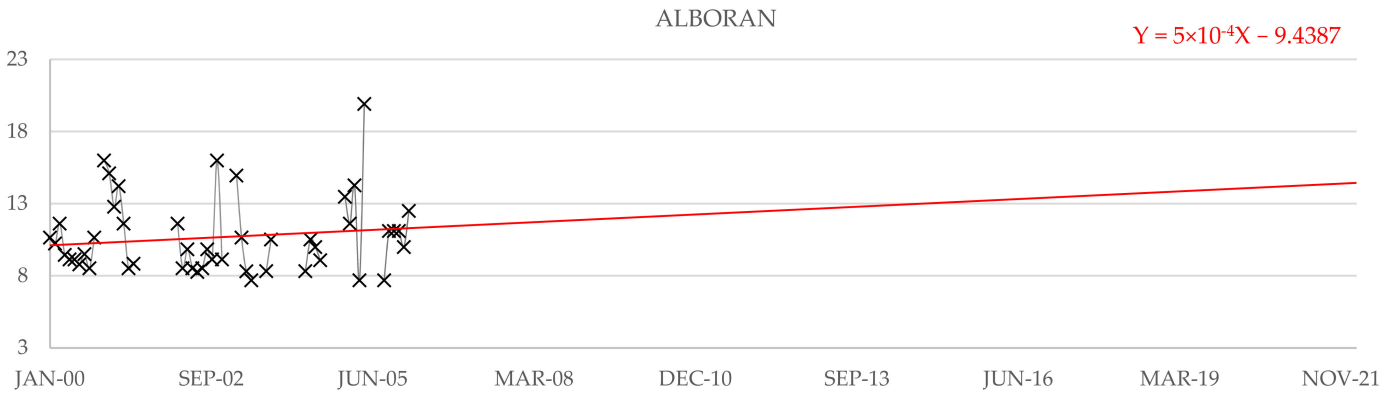


Figure 12. Evolution of Tp maxima in Alboran.

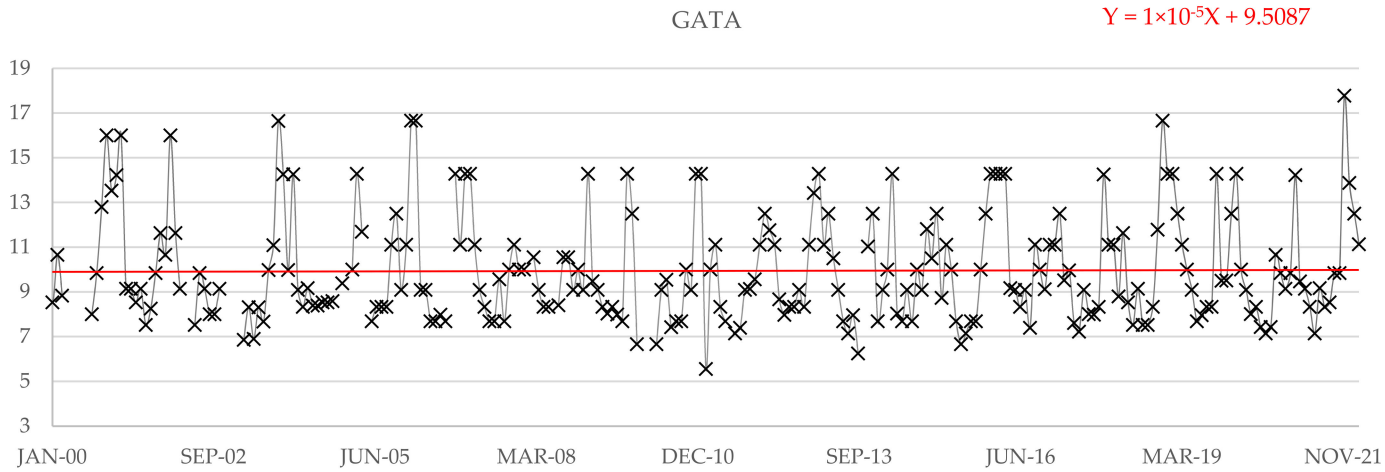


Figure 13. Evolution of Tp maxima in Cabo de Gata.

Table 3 presents the summary of the slopes of the fitted lines of both the Hs and Tp plots. These results will be discussed later in Section 4, as well as their significance in the context of hydroclimatic extremes and future projections.

3.2. Study of Extreme Statistical Parameters

The study of the parameters of the extreme statistical distribution is presented in this section. Figures 19–26 present the number of times Hs has exceeded the exceedance threshold α per year.

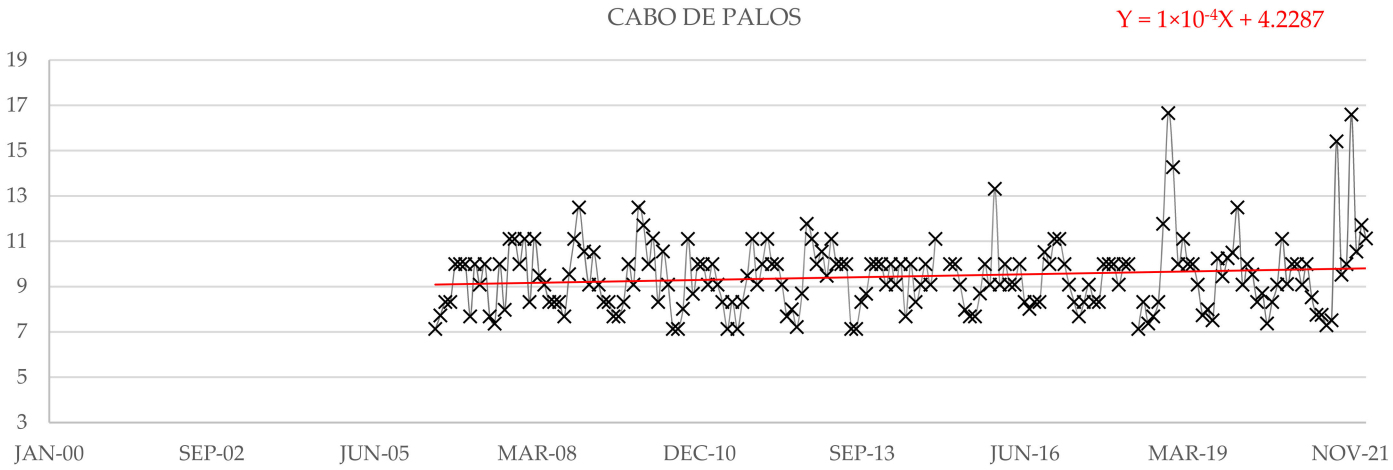


Figure 14. Evolution of Tp maxima in Cabo de Palos.

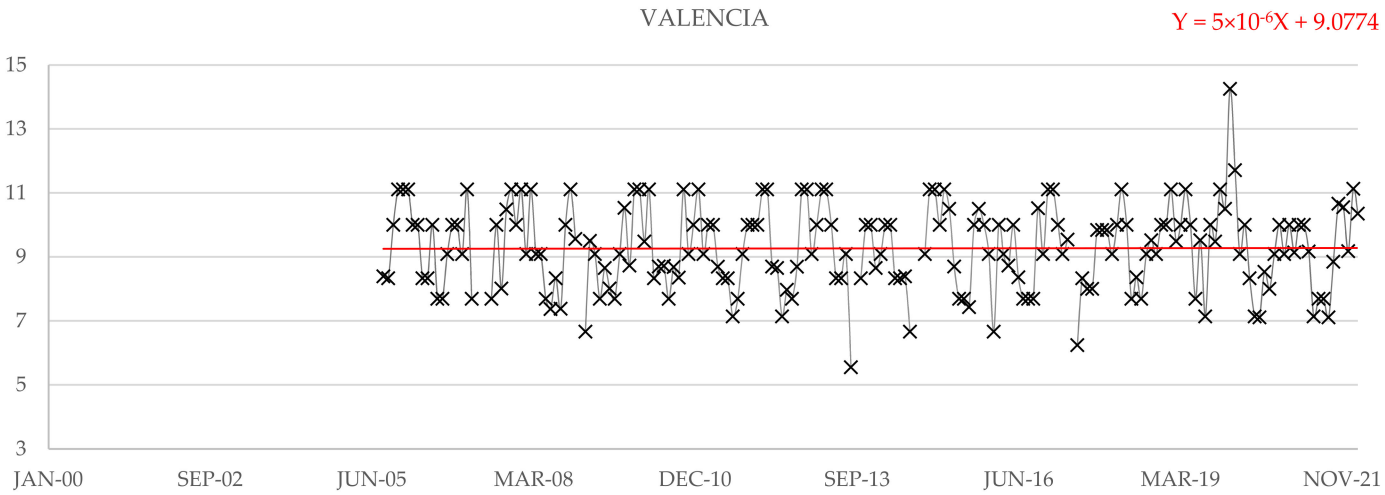


Figure 15. Evolution of Tp maxima in Valencia.

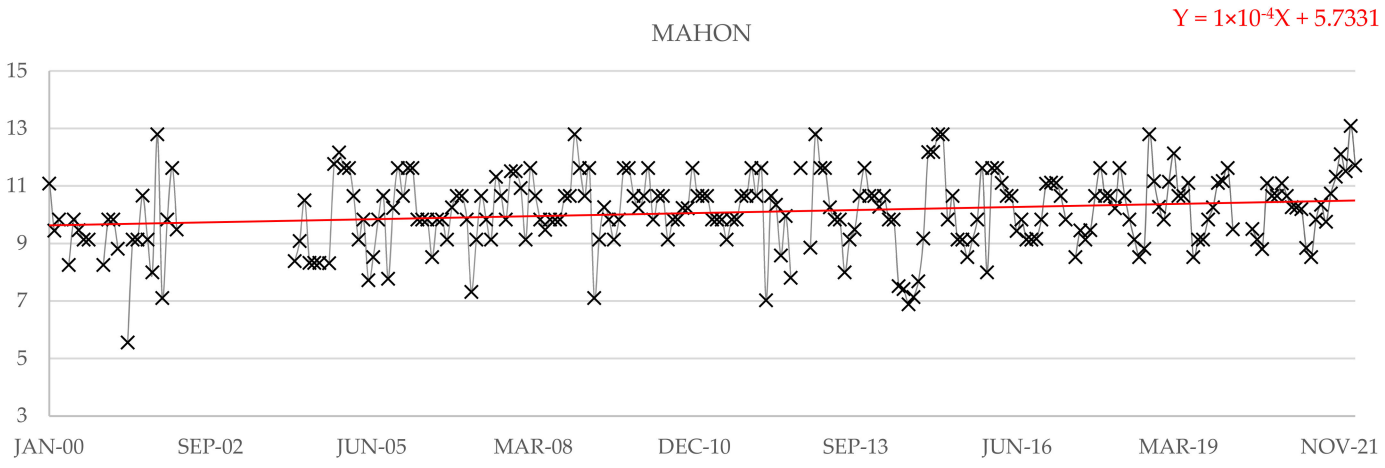


Figure 16. Evolution of Tp maxima in Mahon.

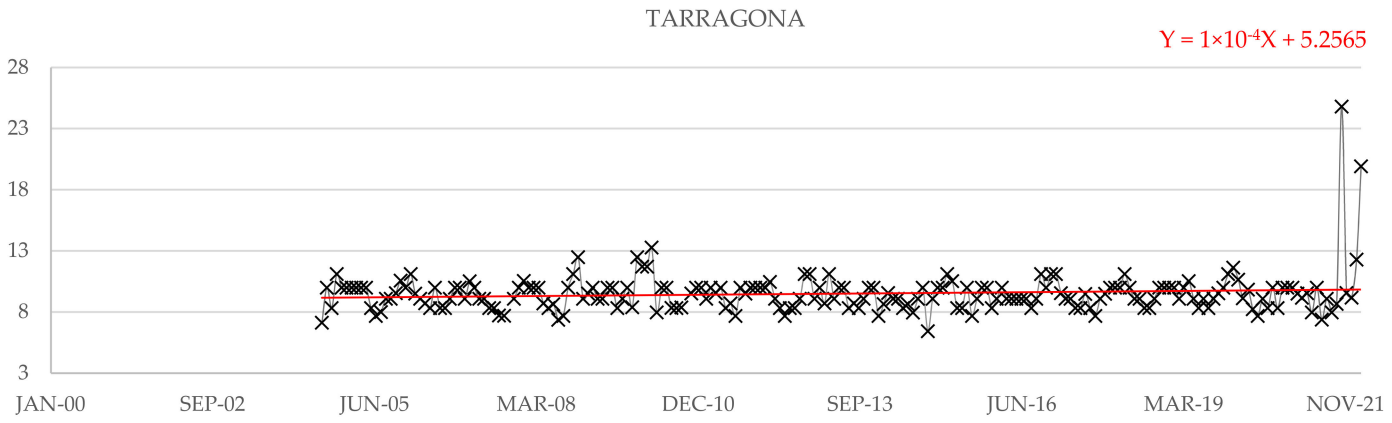


Figure 17. Evolution of Tp maxima in Tarragona.

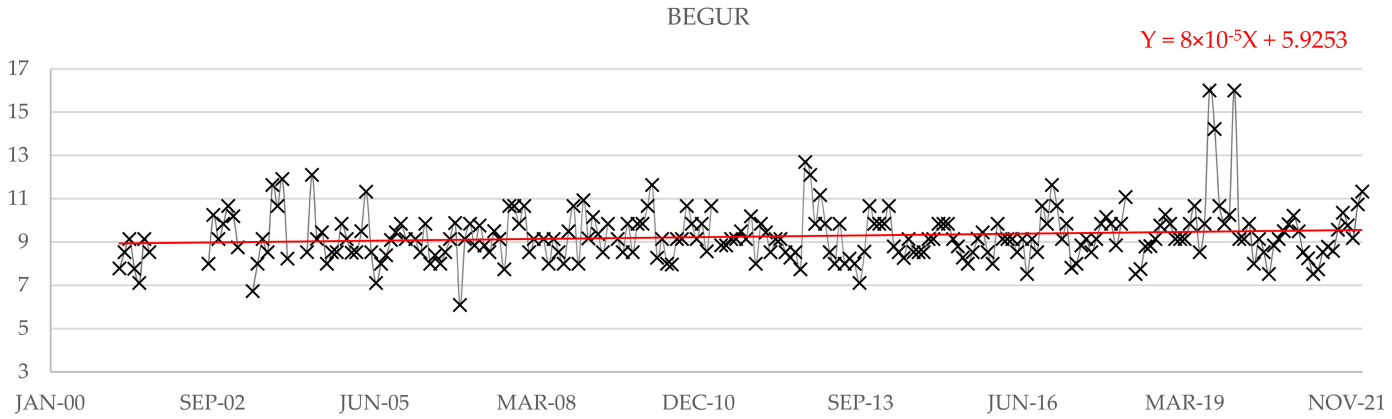


Figure 18. Evolution of Tp maxima in Begur.

Table 3. Summary of Hs and Tp extreme trends for each buoy.

Buoy	Hs Slope	Tp Slope
Gulf of Cadiz	-4×10^{-6}	1×10^{-5}
Alboran	3×10^{-4}	5×10^{-4}
Gata	4×10^{-5}	1×10^{-5}
Cabo de Palos	1×10^{-5}	1×10^{-4}
Valencia	-1×10^{-5}	5×10^{-6}
Mahon	1×10^{-4}	1×10^{-4}
Tarragona	5×10^{-5}	1×10^{-4}
Begur	3×10^{-5}	8×10^{-5}

The Y-axis is the number of exceedances per month, and the X-axis the time. In this section, all the X-axes have also been unified to facilitate the comparison of the different spots. All the figures presented has an X-axis that ranges from 2000 to 2022, even if there were more records or less than the frame of that year. As mentioned above, it was decided to unify all graphs in order to facilitate the interpretation and comparison of the results.

All the figures also present a linear adjustment to facilitate a subsequent trend study of extremes (colour red).

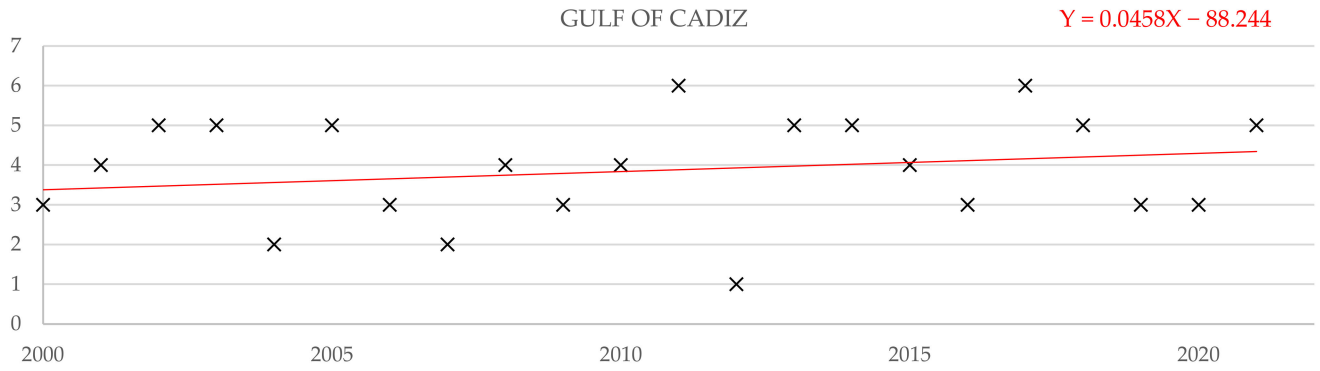


Figure 19. Number of times Hs has exceeded the threshold in the Gulf of Cadiz.



Figure 20. Number of times Hs has exceeded the threshold in Alboran.

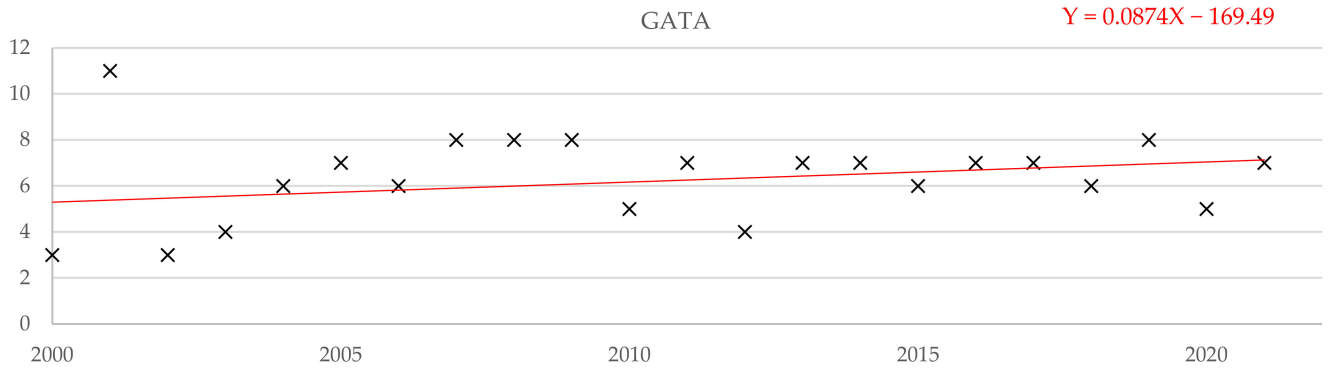


Figure 21. Number of times Hs has exceeded the threshold in Gata.

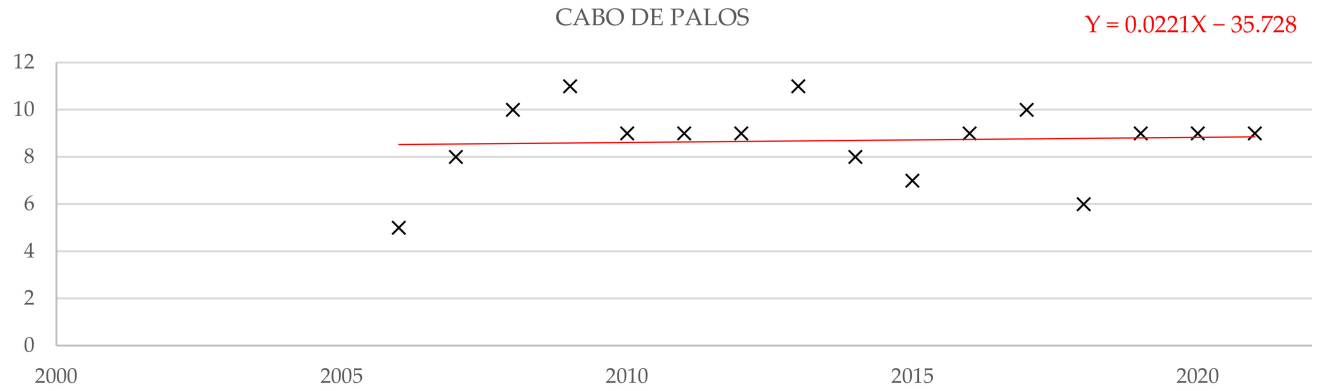


Figure 22. Number of times Hs has exceeded the threshold in Cabo de Palos.

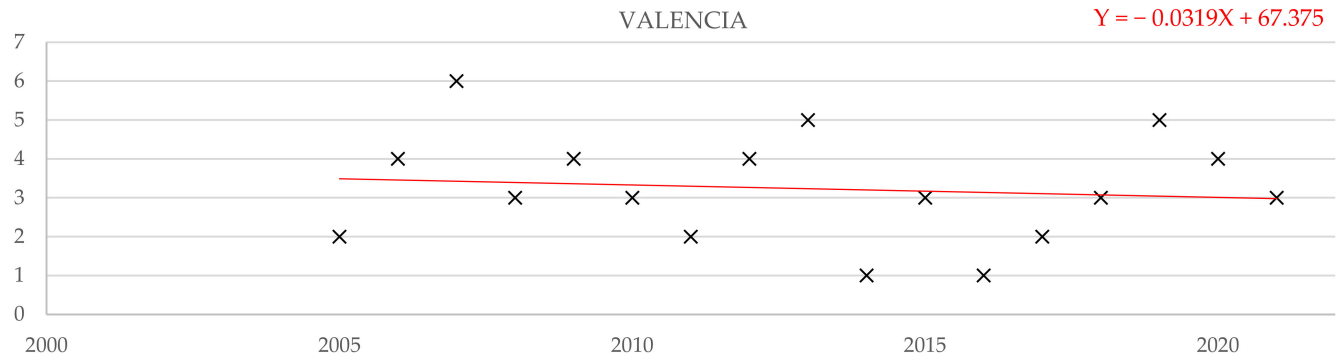


Figure 23. Number of times Hs has exceeded the threshold in Valencia.

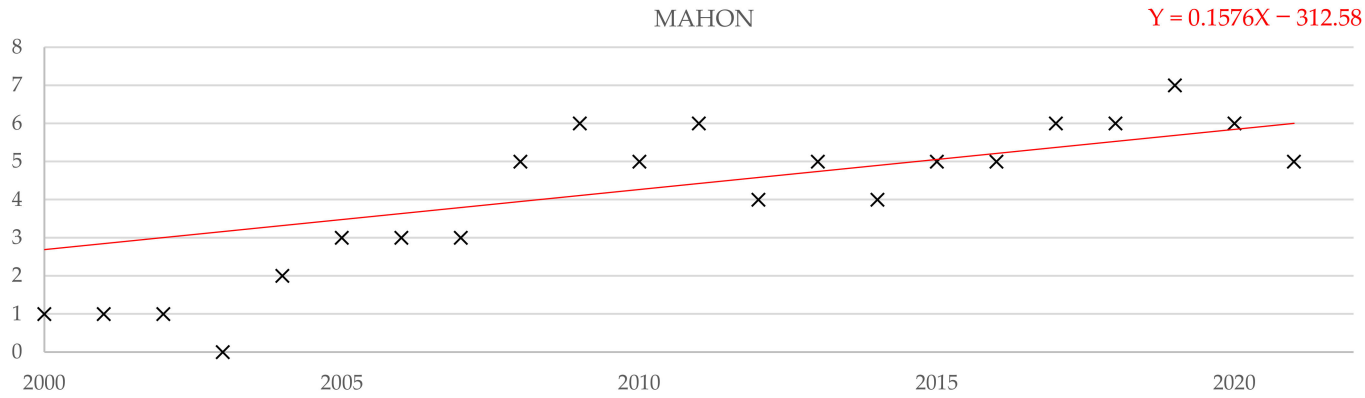


Figure 24. Number of times Hs has exceeded the threshold in Mahon.

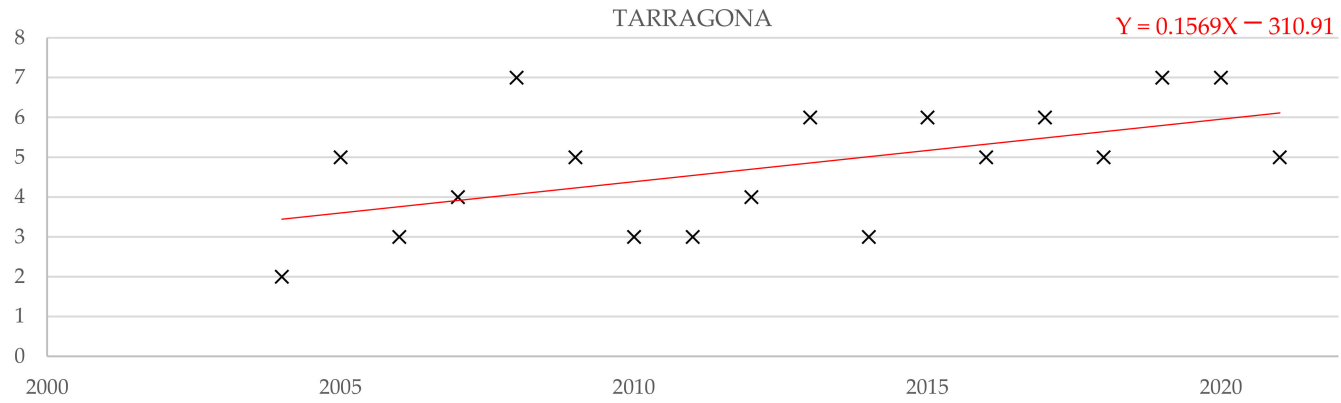


Figure 25. Number of times Hs has exceeded the threshold in Tarragona.

Figures 27–32 present the times that Tp has exceeded the expected Tp in 100 years. As with Hs, the Y-axis presents the number of exceedances and the X-axis is time, and all X-axes are unified. In addition, all the graphs present a linear adjustment to facilitate the analysis of the trend of the hydroclimatic extremes (colour red). Valencia results are not presented because in the case of this buoy, the Tp in 100 years was only exceeded twice, once in 2019 and once in 2021.

These graphs will be analysed in Section 4. In addition, the parameters α, β, λ and γ per se and the Spanish ports' reports of the years 2010, 2011, 2012, 2014, 2015, 2017 and 2020 have been studied [33]. The results were the following:

In the Gulf of Cadiz, all the parameters remained stable. In Alboran, λ increased and the parameters β and γ were less than one. In Cabo the Gata, λ was slightly increasing, while γ was slightly decreasing and β remained stable. In Cabo de Palos, β and γ were

decreasing and λ was increasing. In Valencia, β and γ were also decreasing and γ was less than one. In Mahon, γ was stable and β decreased. In Tarragona, both γ and β decreased and γ was less than one too. In Begur, γ was stable and β decreased.

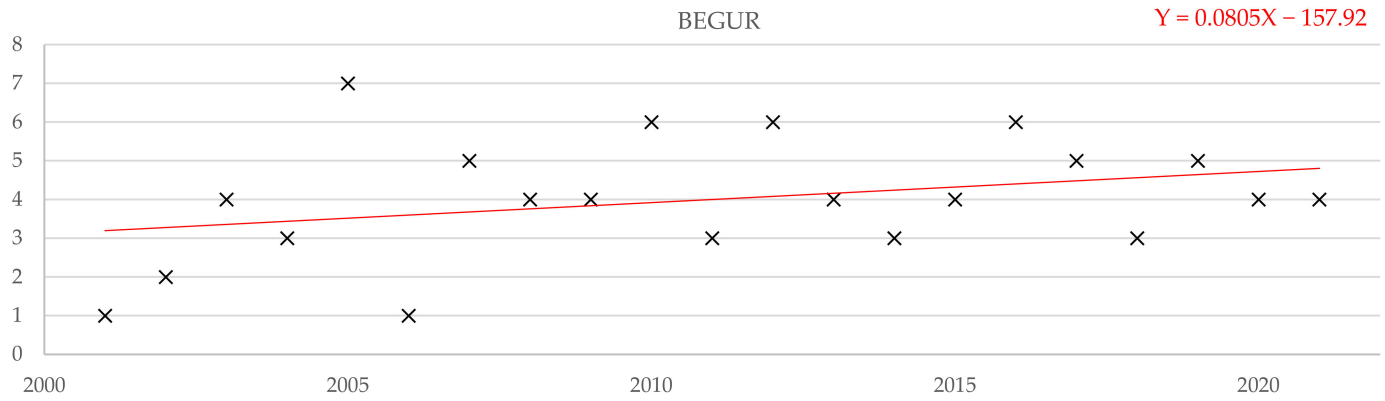


Figure 26. Number of times Hs has exceeded the threshold in Begur.

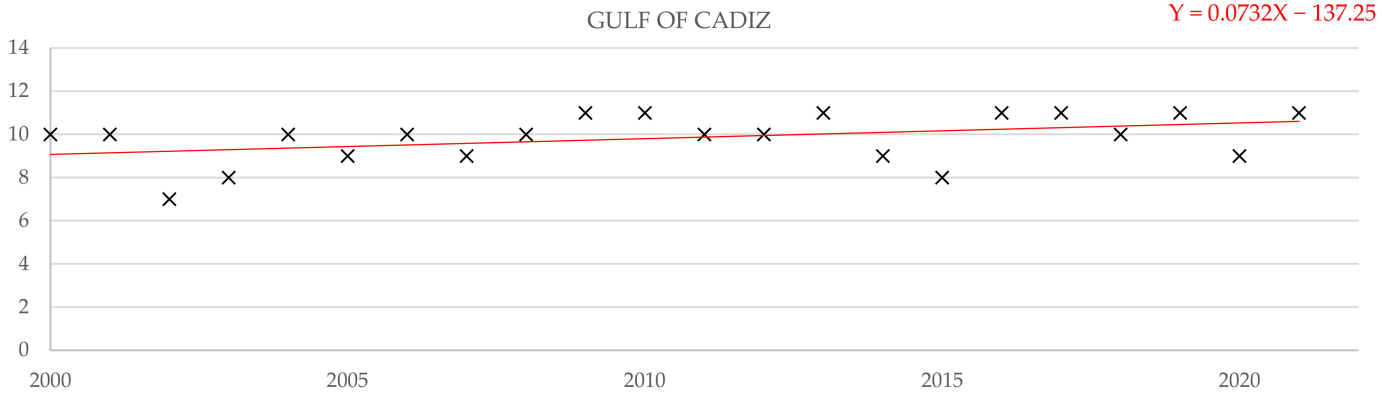


Figure 27. Number of times Tp has exceeded the expected Tp in 100 years in the Gulf of Cadiz.



Figure 28. Number of times Tp has exceeded the expected Tp in 100 years in Alboran.

It has to be said that the reports of the different years of Gata and Begur had different initial years, which may alter the final results when comparing reports from one year to the next.

3.3. Study of SL Monthly Extremes

In this section, the evolution of the monthly maximums of SL in each tide gauge is presented from Figures 33–40. It is structured as the previous sections:

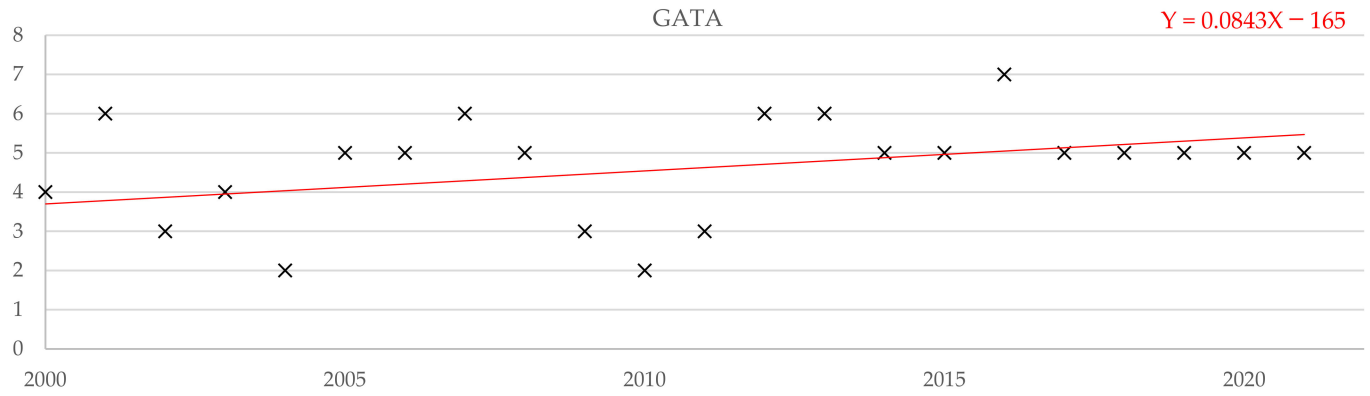


Figure 29. Number of times Tp has exceeded the expected Tp in 100 years in Gata.



Figure 30. Number of times Tp has exceeded the expected Tp in 100 years in Mahon.

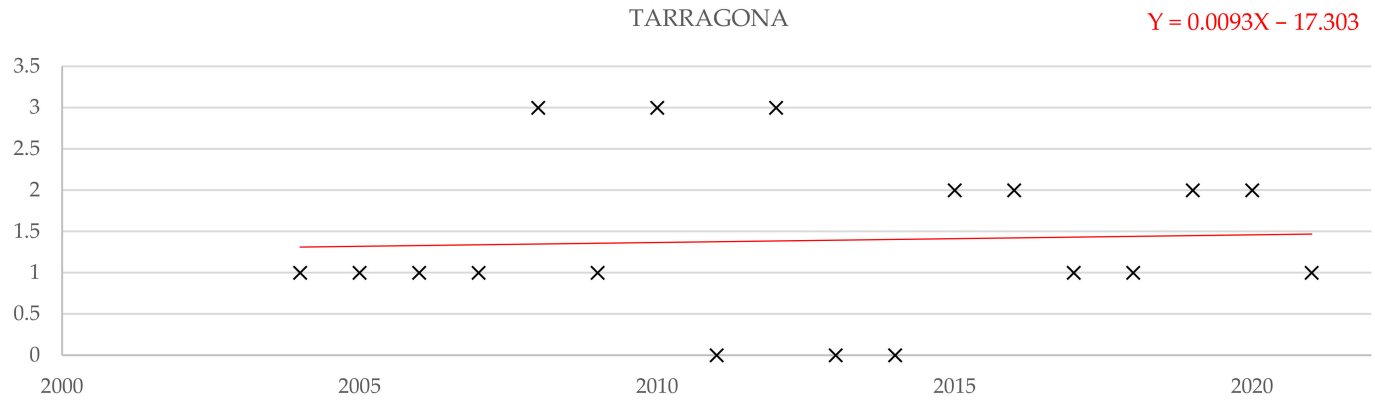


Figure 31. Number of times Tp has exceeded the expected Tp in 100 years in Tarragona.

The Y-axis is the SL extremes in m, and the X-axis the time. The X-axes of all the graphs is unified from January 2006 to December 2020. Each graph also shows the trend line (colour red).

In Table 4, the slope of each tide gauge is presented, which is basically the trend of the SL. This will be further explained in Section 4.

3.4. Correlation of Hydroclimatic Extremes

The correlation of SL and Hs maxima has also been studied. Only the correlation in which deep buoys were available has been studied. Therefore, the correlation of maxima in Tarifa and Algeciras have not been analysed, because it was considered that, as

the buoys were not in deep water, the results were not reliable. Graphs are presented from Figures 41–46.

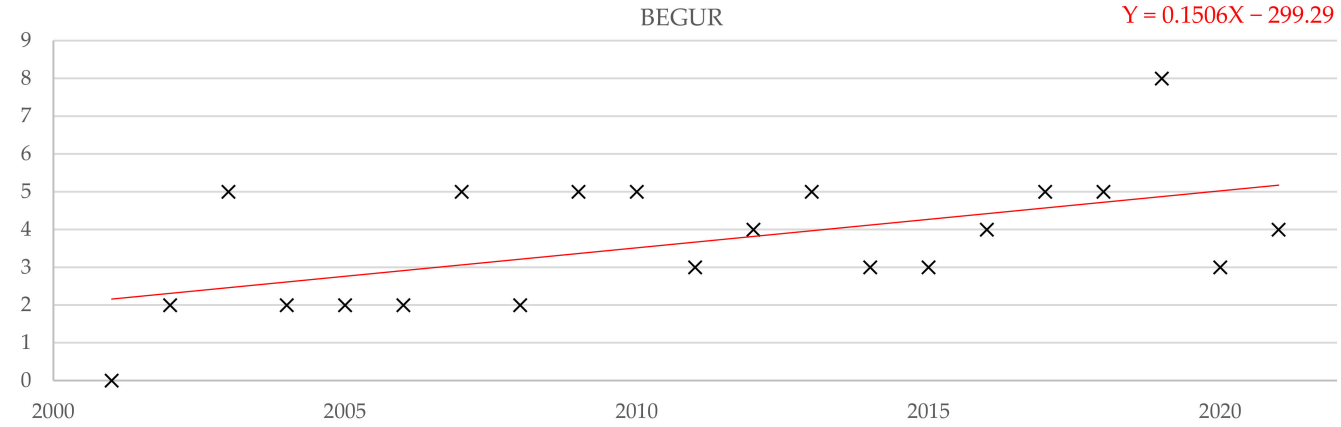


Figure 32. Number of times Tp has exceeded the expected Tp in 100 years in Begur.

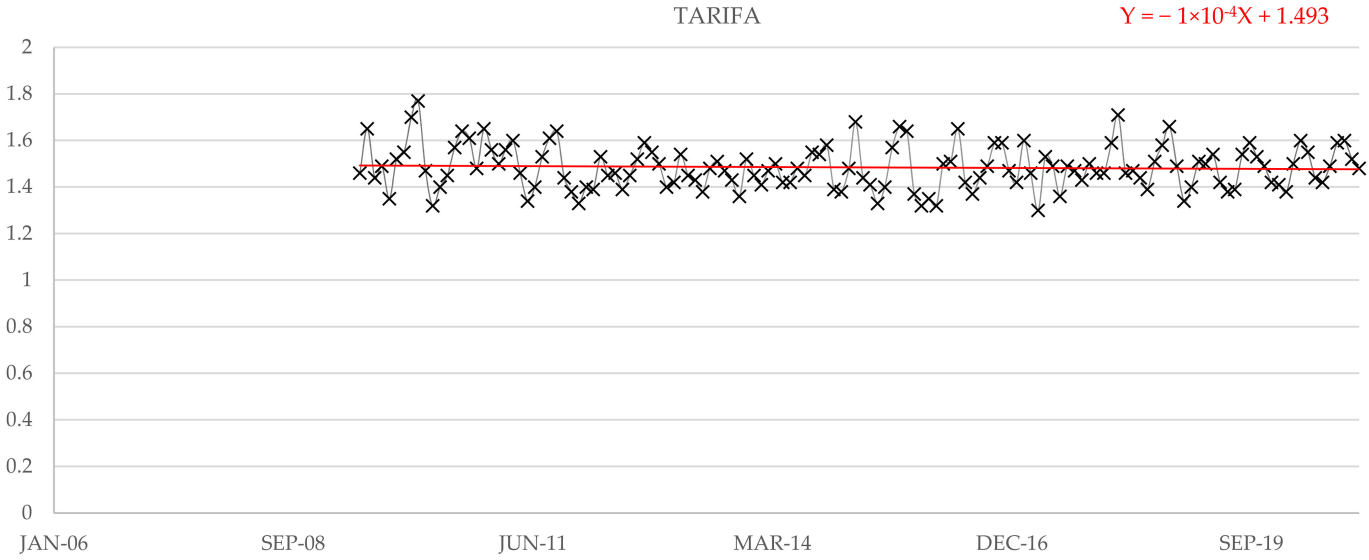


Figure 33. Evolution of SL maxima in Tarifa.

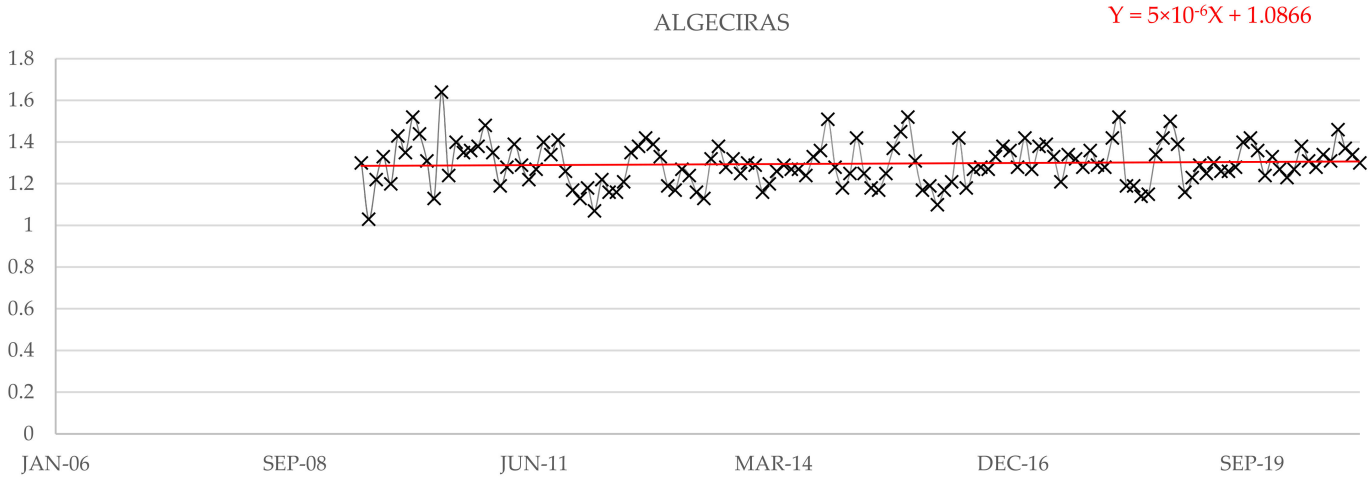


Figure 34. Evolution of SL maxima in Algeciras.

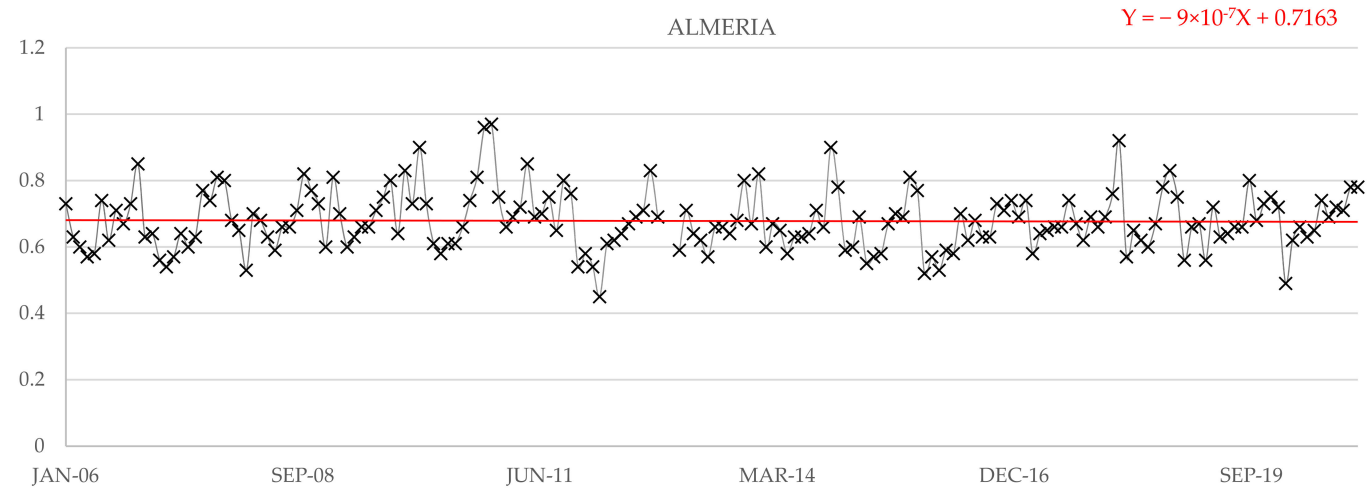


Figure 35. Evolution of SL maxima in Almeria.

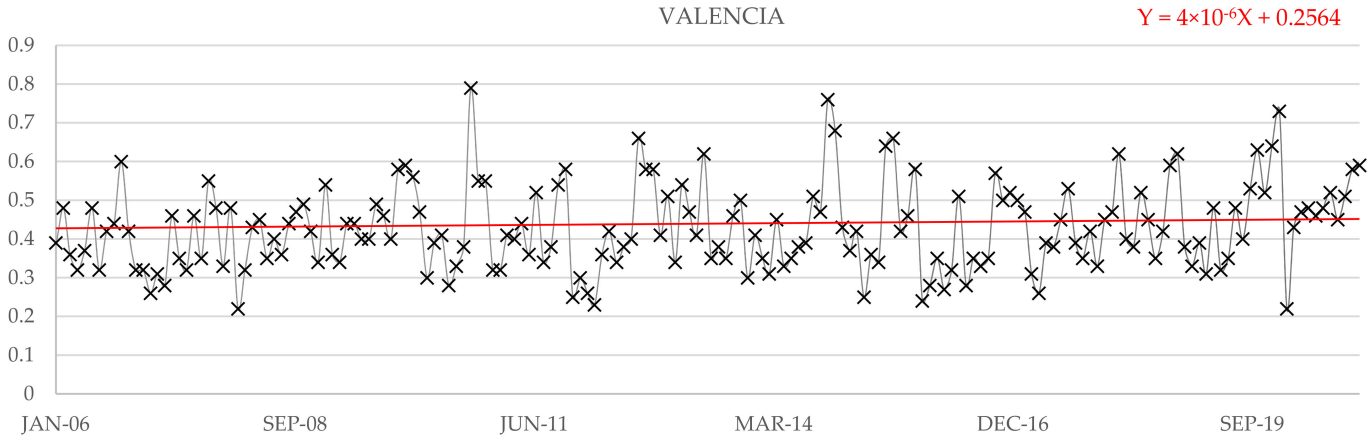


Figure 36. Evolution of SL maxima in Valencia.

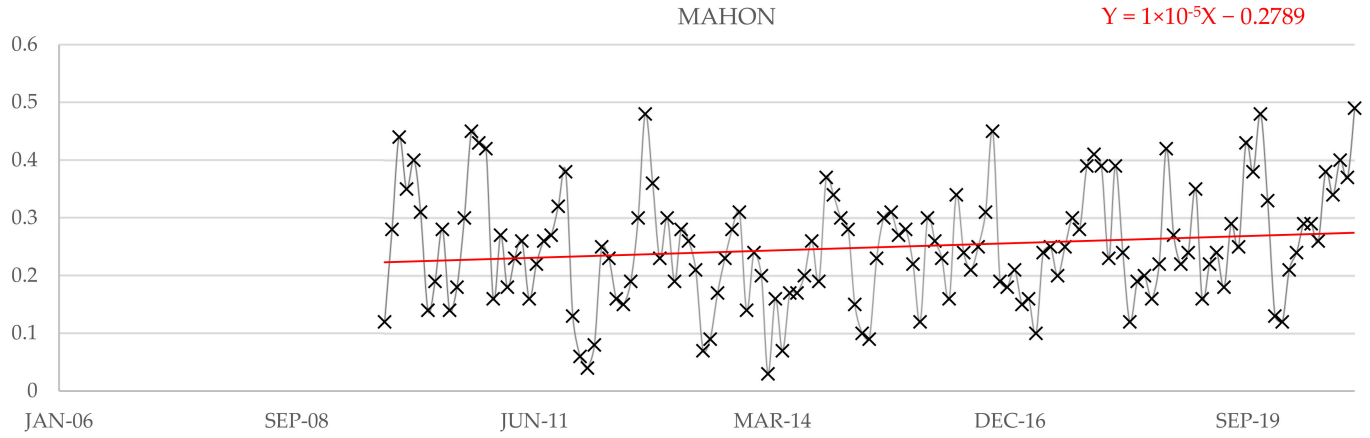


Figure 37. Evolution of SL maxima in Mahon.

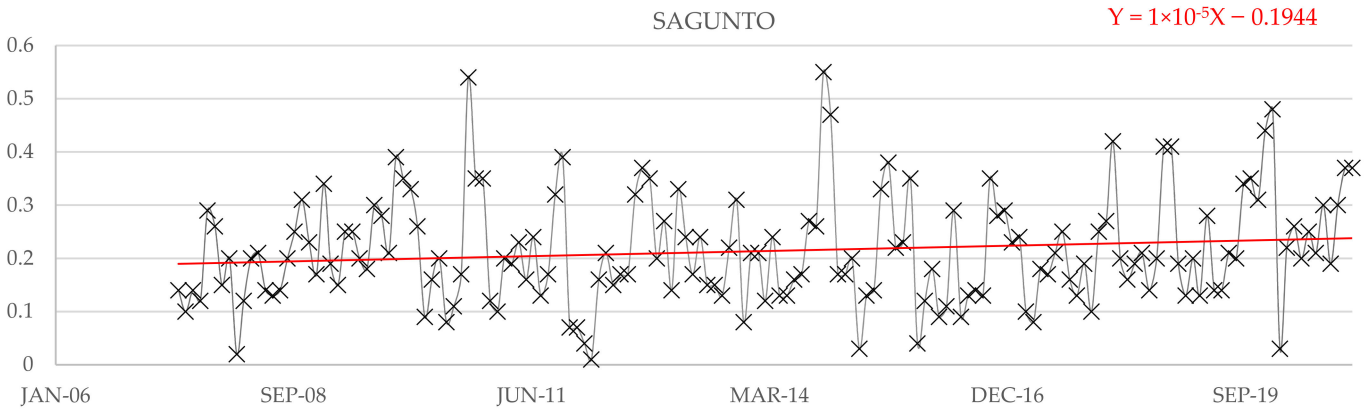


Figure 38. Evolution of SL maxima in Sagunto.

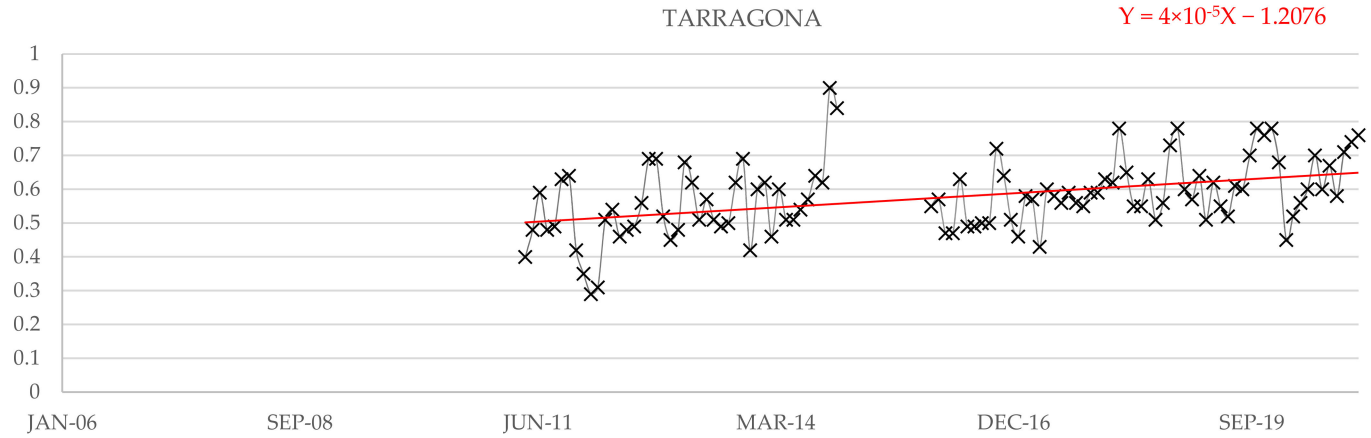


Figure 39. Evolution of SL maxima in Tarragona from 2011 to 2020.

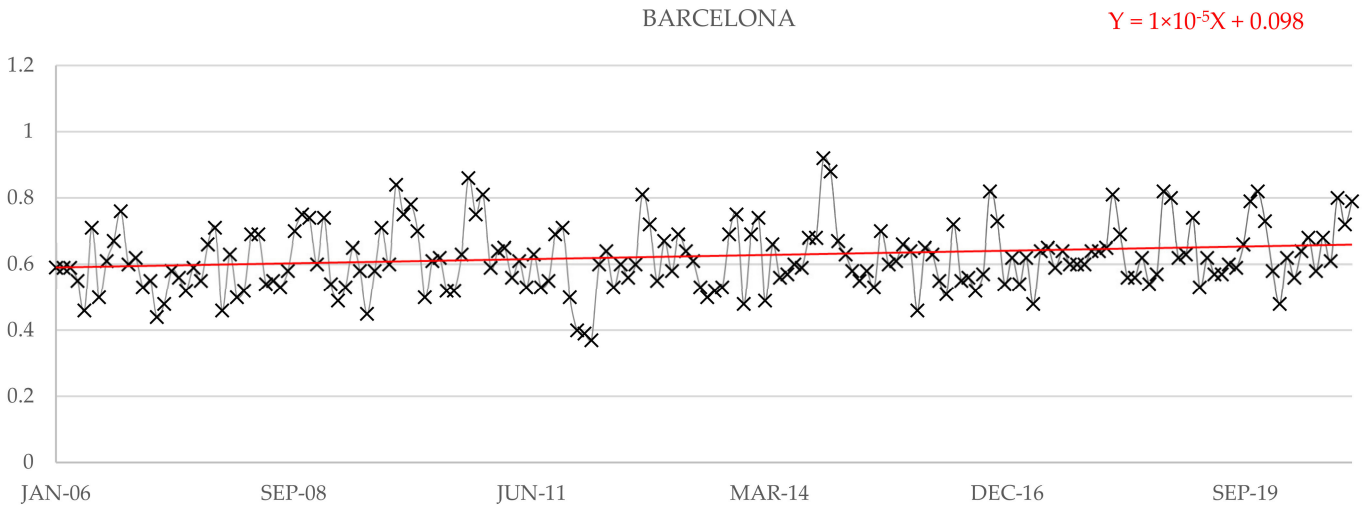


Figure 40. Evolution of SL maxima in Barcelona.

Table 4. Summary of SL slopes.

Tide Gauge	SL Slope
1. Tarifa	-1×10^{-4}
2. Algeciras	5×10^{-6}

Table 4. *Cont.*

Tide Gauge	SL Slope
3. Almeria	-9×10^{-7}
4. Valencia	4×10^{-6}
5. Mahon	1×10^{-5}
6. Sagunto	1×10^{-5}
7. Tarragona	4×10^{-5}
8. Barcelona	1×10^{-5}

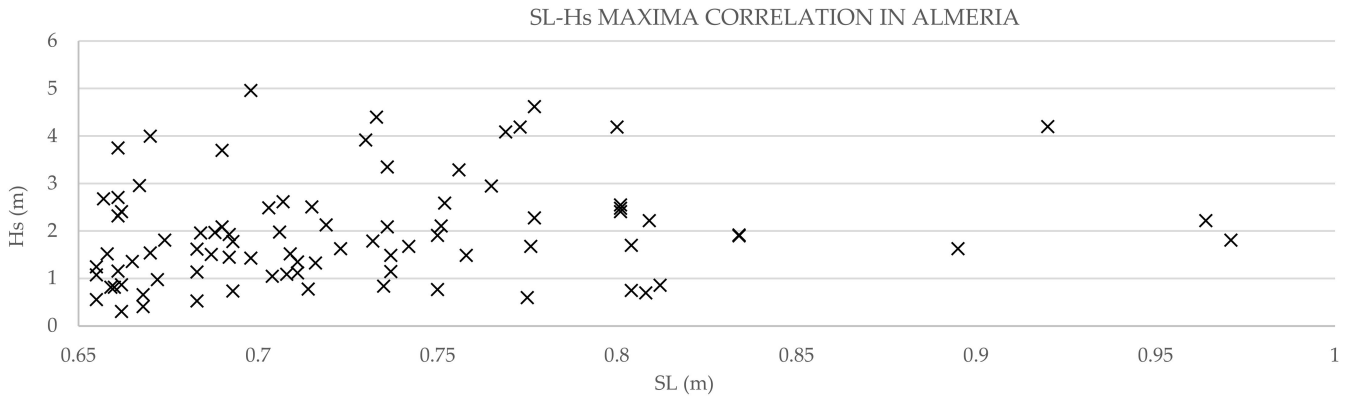


Figure 41. Correlation of extremes in Almeria.

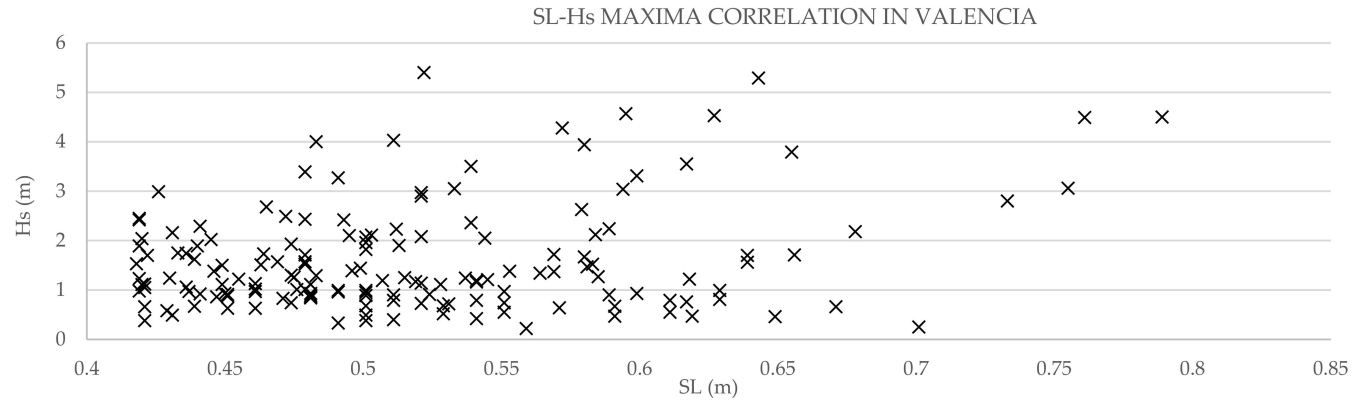


Figure 42. Correlation of extremes in Valencia.

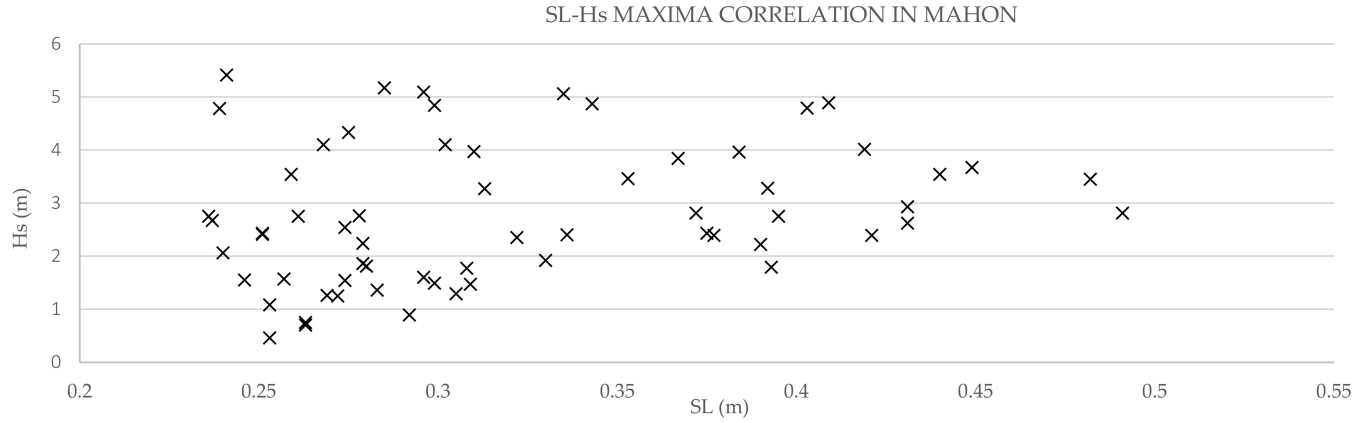


Figure 43. Correlation of extremes in Mahon.

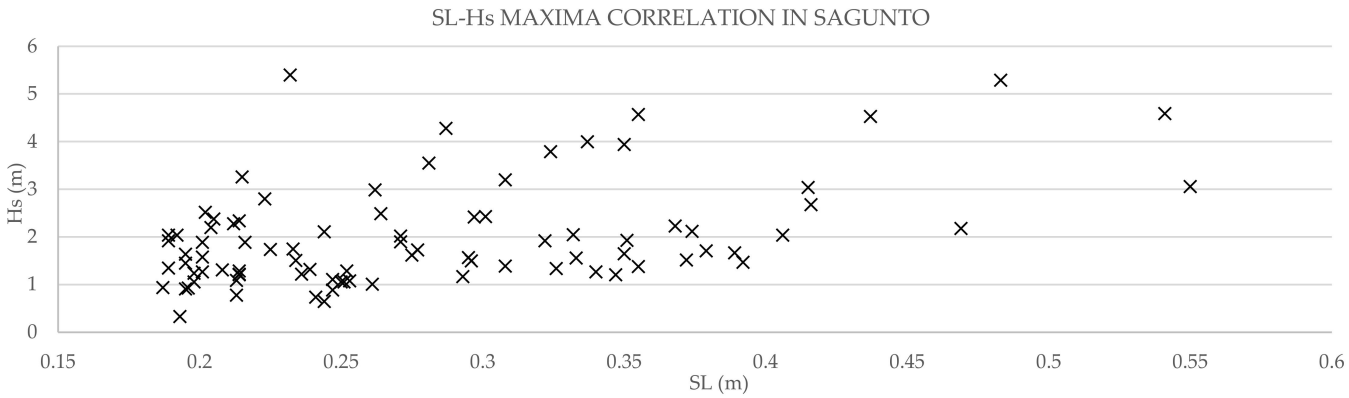


Figure 44. Correlation of extremes in Sagunto.

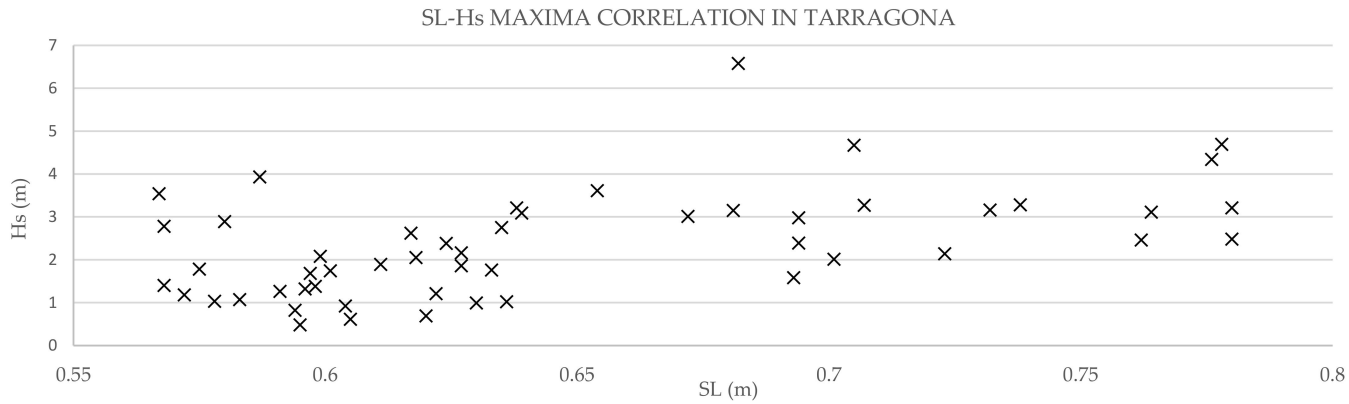


Figure 45. Correlation of extremes in Tarragona.

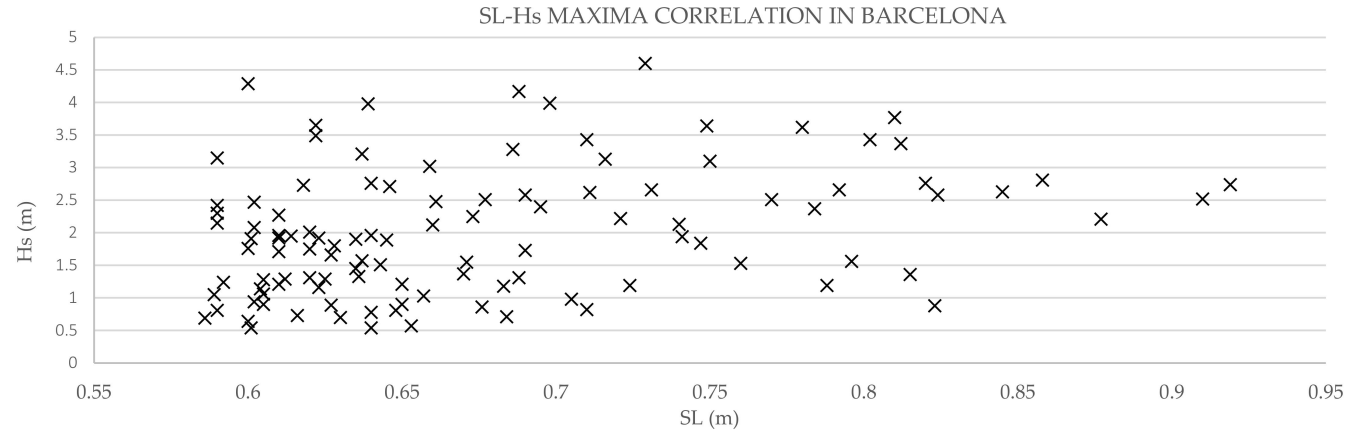


Figure 46. Correlation of extremes in Barcelona.

4. Discussion

4.1. Discussion of Hs and Tp Monthly Extremes

After analysing Hs and Tp plots (Figures 3–18), it can be seen that, referring to Hs extremes, all had an increasing trend, except for the area of the Gulf of Cadiz and Valencia, which had a slightly decreasing tendency. When talking about Tp, all the buoys had also a rising tendency and, the increase of Tp extremes was quicker than the increase of Hs, which is related to the results of Section 3.2.

The Alboran graph (Figure 4) is one of the graphs with the steepest trend line in Hs extremes (0.0003 slope). This is probably because the records of the Alboran Sea buoy are from 1997 to 2006. From 2006 onwards there are no more records. If there were records from

2006 to 2022, the increasing trend line would probably be much smoother. Furthermore, the Alboran Sea is an area affected by local and regional phenomena due to its position. It is an enclosed sea where the wave and wind patterns are very particular, so part of this increasing trend may also be due to these local phenomena and not just to the data series.

Mahon is the other spot where the increasing trend is sharper (0.0001 slope). In this buoy, the problem of the records does not exist. Therefore, this increasing trend can be taken with a high level of certainty, as the records reach from 1993 to 2022. The fact that Hs is increasing more sharply here than in the rest of the Spanish Mediterranean coast is likely due to the wave and wind patterns of this particular area. This clear increasing trend in Hs highlights the need for further studies of climate extremes in this area.

From Cabo de Gata to Begur (Figures 5–7, 9 and 10), the increasing trend of Hs is similar (around 10^{-4}–10^{-5}), excepting the Valencia buoy, which has a slightly decreasing trend. This area may be affected by the same meteorological regional patterns and fluid dynamics. The increasing trend is not as pronounced as in Alboran or Mahon. However, it has to be said that although the trend is less upward, this does not mean that this area is less threatened by extreme events. Although the general trend is less abrupt, this area is prone to very specific but very intense events, as can be seen in the graphs for the 2018 and 2020 storm (Emma and Gloria storm), which far exceeds the rest of the extreme storms. In fact, these "very extreme" events are the most damaging and threatening, and this part of the coast is especially vulnerable to extreme storms. This is also the main reason why the data of these graphs seem to be very scattered, because in this area hydroclimatic extremes are very occasional and intense.

Referring to the Tp climate variables, the conclusions are the same as with Hs. The only difference, as noted above, is that the increasing trend of Tp is more pronounced than that of Hs. This makes sense since Hs and Tp are related, according to the expression $Tp = a*Hs^b$.

4.2. Discussion of Extreme Statistical Parameters

The wave height threshold was typically exceeded in 30% of cases. The wave heights for 20, 50 and 100 years were exceeded at most once in the entire data series, while with the peak periods, up to 85% of the current data exceeded the expected peak period in 100 years (Gulf of Cadiz). Typically, around 20% of the peak periods of the year exceeded the expected 100-year peak period, which is a representative percentage considering that Tp is the Tp expected in 100 years. The fact that a 20% of the current maxima overpasses the Tp expected in 100 years is proof that the estimated Tp for 100 years already exists in current temperature due to the effect of climate change on extreme hydroclimatic phenomena.

The Hs for 20, 50 and 100 years was rarely exceeded in all the spots studies, but the Tp estimated for 20, 50 and 100 years from now was exceeded in some cases by up to 85% of the monthly maxima. This also shows that a statistical readjustment of this variable Tp is already necessary, as the current values do not accurately represent the extreme Tp. Although the increase in Hs may not be significant, the increase in Tp is significant and an adjustment of the statistical values and parameters is needed to adjust the models to the new reality. If this is not carried out, climate modelling and future projections will become increasingly inaccurate.

Referring to the specific spots studied. The Gulf of Cadiz is one of the buoys that need a more urgent adjustment of the Tp statistical distribution, as the estimated Tp 100 years from now was already exceeded in the 85% of the extreme storms. Valencia, on the contrary, has very well adjusted Tp parameters and the Tp in 20, 50 and 1000 years was hardly exceeded. Tarragona and Mahon are other spots that could be said to be well-adjusted, as the 100-year Tp was only exceeded in 10% of the extreme storms. Finally, the area of Valencia would also need a revision of the statistical parameters but the number of exceedances is not as high as in Cadiz.

4.3. Discussion of SL Monthly Extremes

Referring to SL results, almost all the tide gauges showed an increase in sea level. However, it is striking that the tide gauge at Tarifa shows an appreciable drop in sea level, which may be due to regional effects in the area and would need to be studied in more depth in order to reach reliable conclusions.

As is logical, the area where the maximum sea levels vary the most is the area from Cadiz to Almeria due to the astronomical tides. On the other hand, there is the area of Valencia and Cabo de Palos, whose tidal range is 0. Here, even though the tide is practically nil, it can be seen that sea level peaks are also reached very occasionally, following a similar behaviour to that explained by Hs and Tp extremes in Section 4.1., which increase the vulnerability of these areas to hydroclimatic extreme events. If concomitant extreme events (Hs, Tp and SL) occur in this area, the damage and losses can be devastating, as extreme events in this area of the Mediterranean are very intense. This will be further discussed in the next subsection.

Finally, referring to the area of Barcelona and Tarragona, SL maxima variability is also higher because of the tides.

The general pattern is that SL maxima are increasing, as has been proven by the scientific community. The area where this increasing trend is sharper is the Levantine basin, which makes it more vulnerable to extreme storms, as this paper has already stated.

4.4. Discussion of the Correlation of the Hydroclimatic Extremes

Finally, the correlation of Hs and SL was analysed. As mentioned in the previous subsection, assessing the concomitance and correlation of hydroclimatic extremes is essential to avoid future damage. In addition, the Levant Mediterranean area is particularly vulnerable to occasional, but very intense, extreme events.

In Almeria, extreme SL were associated mostly with medium waves, while extreme waves happened with medium SL.

In Valencia, Mahon and Sagunto, extreme SL occurred with relatively high waves, which should be considered in future designs so as not to underestimate extremes and their concomitance. The fact that extreme events in this area can be concomitant further aggravates their situation, as they already have a devastating effect on their own. If maximums of all three variables were to occur at the same time, the damage could be even greater, which requires specific studies in the Levante area.

In Barcelona and Tarragona, the concomitance of the hydroclimatic extremes were not as clear as in the Levantine basin with Valencia, Mahon and Sagunto, but it can be appreciated how some of the highest waves and SL also occurred with relatively high SL or waves, respectively. However, it is not as relevant as it is in the Levantine basin.

5. Conclusions

After analysing and discussing all the results, several conclusions can be highlighted.

Mahon and Alboran are the spots in the Spanish Mediterranean were the increasing trend of Hs and Tp extremes is sharper. This increasing trend can be taken with a high level of certainty in Mahon and with a medium level of certainty in Alboran due to the short-period data frame.

Although the increasing trend of Hs maxima in the Levantine basin is not as sharp as in other parts of the Spanish Mediterranean coast, it is subjected to the most intense one-off events. These events are the ones that cause the most damage, making the Spanish Levante region particularly vulnerable to extreme hydroclimatic events.

A readjustment of the Tp statistical parameter is needed. Expected Tp for 100 years is reached in more than 20% of extreme storms in most of the spots studied, which means that the estimated Tp for within 100 years is already happening. The most critical spot is the Gulf of Cadiz with an 85% of exceedance.

SL is increasing along all the Spanish Mediterranean coast, excepting Tarifa, which may be due to local phenomena. The behaviour is very similar to Hs and Tp extreme events but affected by the astronomical tide.

The area with the highest concomitance of extreme events is the Levantine basin. Having SL, Hs and Tp extreme events at the same time would be devastating. Therefore, more in-depth studies on the coast from Valencia to Cabo de Palos are needed, and even more so considering that this is the area of the Spanish coast where the fewest scientific studies have been carried out.

Considering all these conclusions, future research directions should focus on studying the concomitance of hydroclimatic extreme events (Hs, Tp and SL) in the Levantine basin and in the adjustment of statistical Tp parameters.

Author Contributions: This paper will be included in the PhD thesis developed by Nerea Portillo at the Technical University of Madrid, Spain, and the aim of the research relates to reviewing climate change and its impact on ports and its adaptation, carried out by the PhD candidate. All the authors contributed toward choosing data, discussion, methodology, figures and references to provide an accurate paper. Conceptualization, N.P.J. and V.N.V.; Funding acquisition, N.P.J.; Investigation, N.P.J., V.N.V. and J.M.d.C.; Methodology, N.P.J. and V.N.V.; Writing—original draft, N.P.J.; Writing—review and editing, N.P.J., V.N.V. and J.M.d.C. All authors have read and agreed to the published version of the manuscript.

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