Dear Referees,

Thank you so much for reviewing our paper.

The manuscript will be, therefore, modified to consider your constructive comments. In the following, a point-by-point response to your comments will be presented.

The authors,

Point-by-Point response / reviewer # 1

Comment	Responses to comments
General point 1: Too many details are sometimes given in points that are not further elaborated upon in the manuscript and on the opposite some critical information on the methods is missing. For example, the authors start the manuscript by discussing about nuclear power plant but this is not discussed further in the text other than they should not change the reference method. This seems to discredit the whole idea behind the need to compare and discuss different methods.	This is an interesting comment. The NPPs example is used as a motivation element. Yes, indeed, this work is done in a context of nuclear safety and review of the nuclear safety demonstration and protections. This was mentioned in the introduction section. It was also mentioned that the present work could be used to enrich safety verification approaches. It's also true that we don't aim to modify the reference method in the present work but attempt to propose other approaches, and simply confront all of them. This is now clearly indicated in Sect. 1, page 2, lines 40-42 "The present work could be used to enrich safety verification methods by proposing other approaches and confronting them to the reference method currently used in the guide"
General comment 2: In the introduction, the authors discuss at length different types of other hazards happening in coastal areas (pluvial, fluvial floods) but this is not further looked into in the paper. If I understood correctly, the present study is on extreme sea levels and therefore extensively discussing about pluvial and fluvial floods seems out of the scope in my opinion. Similarly, it was not clear to me why the authors present in Table 1 the rainfall datasets if this is not used in this study.	We agree that discussing other flooding sources was a bit exaggerated. A part of this discussion is now removed. Rainfall data characteristics are likewise removed from table 1.
There may be a general point to make that including statistical dependence is important to include when estimating (coastal) hazard but I am not sure why the authors put so much emphasis on this point if they don't themselves assess this statistical dependence in their selected case study. Throughout the paper, it is assumed that the tide and storm surge are independent but the authors never report on the validity of their assumption by reporting this statistical dependence. A good example	The comment is on matters of substance. Yes, indeed, it is always interesting to quantify the statistical dependence in a context of coastal flooding. In another work, we combined the storm surge with other flood phenomena (riverine flooding and/or local rainfall, etc.) and the correlation of the variables of interest was evaluated. The statistical dependence was measured with a Chi-plot technique and non-parametric estimators (the upper tail dependence, for instance). This allowed us to decide modelling the dependence structure of the two variables using the copula theory (when they are dependent) and to only consider the univariate CDF's in case of independence. Indeed, we did not aim in the present work to show details on how evaluating the dependence in extreme value context.

of locations where this assumption might or might not be correct is given in Sterl, A., van den Brink, H., de Vries, H., Haarsma, R., and van Meijgaard, E.: An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate, Ocean Sci., 5, 369–378, https://doi.org/10.5194/os-5-369-2009, 2009.	Indeed, the general goal of the present paper is to characterize the hazard "coastal flooding" by combining the high-tide and extreme storm surges (SSSs & MSSs). A dependence analysis was conducted despite the fact that the study aims to use only the extreme values of these variables. Scatter graphs and the Spearman's Rho have been used to measure the statistical dependence between high-tide and extreme SSs. It was concluded that this dependence is weak and sufficiently low to consider the variables of interest dependents. The following sentence is now used: - In the Abstract (lines 11-12) : "Most existing studies are generally based on the assumption that high-tides and extreme SSs are independent." - In the Methods section (lines 147-148): "Indeed, as mentioned in the introductory section and as it will be discussed later in this paper, extreme levels such as MSSs may be only very weakly dependent with high-tides." The discussion section (lines 291-293 and 302-308 with figure 7) has been changed to add a discussion on the dependence analysis. Another kind of dependence that caught our attention (but more important for the coincidence model) is the one between the high-tide and the other instantaneous storm surges around the high-tide (±6 hours). The Spearman's Rho was used as a measure of this statistical dependence (a further discussion section is now added to the paper).
At multiple points in the paper, the authors successively mention that dependence is not important but also that it could be important. These two statements, without further results or analysis, seem contradictory. For example page 3 – line 108-109: "Unlike to what is done very often in the literature, the question of dependency is not essential at all to combine phenomena in the present work. Indeed, as mentioned in the introductory section, tidal signals and SSs are independent." and later page 8 –line 283-284 "It has also been suggested that the questions of coincidence and dependency are essential for a combined tide and SS hazard analysis."	It was assumed in the present paper that the tide and storm surge are independent and a convolution model has been applied with a simple sum of them in the indirect method (with both, skew storm surges and instantaneous ones). I must admit that there is a contradiction here. The two sentences are now modified: Lines 145-147: "As it would be analyzed later in the discussion section, the dependency, in an extreme value context, is analyzed but not considered to combine the phenomena in the present work." The second sentence has been removed to the beginning of the conclusion section. "It has been suggested that the questions of combining tide and SSs is essential to better characterize the coastal flooding hazard." In addition, as suggested by one of the reviewers, the sentence "Tide and extreme SSs are considered as independent" in the abstract is now replaced by: "Most existing studies are generally based on the assumption that high-tides and extreme SSs are independent." (lines 11-12).
The authors state that the maximum storm surge (MSS) can happen randomly somewhere within the tidal cycle. Again as showed in Sterl et al. (2009), I would argue that this is not the case and that the timing of the maximum storm surge is often closely related to physical properties of the coastal system. If this temporal dependence is present, I believe that the suggested method is likely to overestimate extreme sea levels.	Thank you for this comment and for suggesting the possible explanation. Yes it was assumed that a maximum storm surge can happen randomly somewhere within the tidal cycle. We didn't analyse the relationship that can exist between the timing of the MSS and the physical properties of the coastal system. We however recognize that considering this interaction between the timing of the MSSs and the coastal system is difficult to conduct and further investigations are here necessary.

Table 2 and Figure 4 are not in line while I believe they should report the same values. When reading Table 2 for the 1000 year return period, one reads that MSS > ESL > SSS while when looking at Figure 4 the order is SSS > MSS > ESL. Based on my previous comment, I would suspect that the legend is Figure 4 was incorrectly labelled and that the highest curve shows the method based on the convolution with MSS.	Right, the legend is not correct. It is now correctly labelled. The table has the number 3 and the figure has the number 6 now.
In the discussion, the authors reflect on ways in which the possible dependence between the tide and storm surge and the timing between the latter could be included. The research presented here would greatly improve by actually doing these suggestions.	Very interesting idea. We agree that this will greatly improve the present research. We propose adding a "further discussion" section to take up this reflection (the way in which the possible dependence between tide, storm surge and the timing between them). We included in this new section the following paragraphs: " **6. Further discussion** As show in Figure 6, RLs obtained with the joint MSS-tide method are always higher than those using SSS. This is consistent with the fact that the convolution process based on MSS uses only high water values for the tide density (as it selects the maximum value of instantaneous SSs every 12 hours) and since MSS is always greater than or equal to SSS. It is then logical to consider that the joint MSS-tide method is more conservative than the SSS based one. Figure 6 also shows that extreme sea level events at the right tail of the distribution (the middle curve) tend to occur at the time of the high tide, as expected. The results of this procedure confirm the general finding highlighted in the literature (Fortunato et al., 2016; High et al., 2016) that the return level estimations obtained with the convolution tide-SSS are not adapted up to a certain return period (100 years in the case of Le Havre). To overcome this problem, one can use an empirical method to define the left tail of the distribution and an extreme values analysis for the right tail as stated by Tawn and Vassie (1989). On the other hand, the current practices and statistical approaches to characterize the coastal flooding hazard by estimating extreme storm surges and sea levels still have some weaknesses. Indeed, the combination of the tide and the storm surge do not take into account several scenarios in particular those with a time-lag where the tide and the storm surge could give likewise extreme sea levels. The choice of variables (high-tide, SSSs, MSS, etc.) would be a decisive step and an integral part of the logic behind the idea of combining the two phenomena. Interestingly, these variables could also include other explanatory variables such as the time-lag between the two phenomena (tide and SS). This time-lag would be an additional variable and it is defined as the difference of time of occurrence of the second variable with respect to the first (e.g. time between a maximum storm surge and a high-tide). **6.1 coincidence probability concept** Our interest to the probability of coincidence comes from our belief that a bias is introduced with the joint-MSS convolution because it does not take into account the time difference between the maximum instantaneous SS and the high tide. A probability of coincidence (i.e. the chance that a MSS occurs at the same time with high tide) can be used to better characterize the extreme sea levels using the MSS. In the present paper, we are only interested in the concept of the coincidence probability and the statistical dependence between MSS and tide at the moment of the high-tide and around it (±6 hours). An appropriate coincidence probability concept would then allow to better

estimate the probabilities and thus reduce the bias and bring the RLs closer to those obtained by the reference method.

Let Δ be the time-lag between the high-tide and the MSSs in each tide cycle. When considering coincidence, an additional hazard curve, associated to the variable Δ can be built. The time-lag variable Δ, which would allow us to compute a probability of coincidence, could be involved in a multivariate frequency analysis to consider the dependence structure between the variables. It is also interesting to note that the probability of coincidence would make it possible to conclude if the MSSs occur randomly in a tide cycle or not. The work must be performed for many coastal systems with different physical properties to conclude whether or not there is a systematic temporal dependence, and whether or not the extreme sea levels are overestimated if this is indeed the case.

As shown in the right panel of figure 2 the MSS can occur randomly somewhere around the high tide M_n. The time difference between the MSS and the high tide is random as well. It is therefore quite legitimate to study it with a frequency analysis method. Then a coincidence probability concept can be drawn as follows:

- Extract an independent sample of Δ
- Fit this sample with the appropriate distribution function. “Indeed, Δs is expressed in hours and it is not an extreme variable, it is bounded between -6H and 6H and can take any value with in this interval. There is then no tail of the distribution and the extreme value theory is not the appropriate framework to model this random variable. Thus, a uniform distribution would be a good fit for Δ.
- Use the desired probability to weight the probabilities of the MSSs, assuming that MSSs and Δ are independent. Many scenarios using many of these probabilities can be used in a probabilistic approach.

On the other hand and focusing on the statistical dependence, extreme SSs samples around the high tide (at the time Δ of the high tide) was extracted. The largest window (±6 hour) centered on the time of the high-tide was used and the statistical dependence was then studied. Table 5 shows the Spearman’s Rho measuring the statistical dependence between storm surges and tide at the moment of the high-tide and around it (±3 hour). It can be easily concluded that the dependence between SSs and tides is very high around the time of high tide and it becomes weaker as delta increases. As mentioned in the previous section, the dependence structure that exists between the MSSs around the high tide could be modelled with copulas.

Table 5: Spearman’s Rho calculated between high-tide and all the instantaneous surges in the tidal cycle

Δ	-6	…	-1	+1	+4	+5	+6
High-tide	0.29	…	0.85	0.77	0.44	0.33	0.30

6.2 The non-stationary context

It is noteworthy that the climate change in the past and working in a non-stationary context can greatly affect and invalidate the fit of the storm surge and sea level PDFs. Indeed, questions such as: what is the effect of potential trends and jumps in the sea water level time series? And should this affect the results and its confidence? are fair ones and perfectly justified. The non-stationary context is not covered by this paper because it moves us further away from the main objective which is the use and the confrontation of different methods for quantifying the exceedance probability of extreme sea levels. It could however be the object of another paper."

This paper would highly benefit from having more figures and analysis to make their point clear. For example, it would be interesting to see the studied time-series of Le Havre, examples of extreme events, an analysis of the dependence between the tide and the skew surge and/or and/or the MSS and/or the ESL events.	More figures are now added: - To the section case study: Figure 4. Studied time-series of Le Havre: (top) predicted and observed sea levels; (middle) SSSs data and (bottom) the MSSs. - To the discussion section**:** Figure 7. Analysis of the dependence between the tide and the SSSs, the MSSs and the ESL events.
The authors did not discuss nor report the effect of potential trends and jumps in the sea water level time series. They can greatly affect and invalidate the fit of the pdf and are often present in such time series.	Yes, indeed working in a non-stationary context can greatly affect and invalidate the fit of the storm surge and sea level PDFs. We didn't consider it in this work because we think that it moves us further away from the main objective of the paper. It could however be the object of another paper. The following paragraph is now added to the further discussion section (lines: 363-369) "It is also noteworthy that the climate change in the past and working in a non-stationary context can greatly affect and invalidate the fit of the storm surge and sea level PDFs. Indeed, questions such as: what is the effect of potential trends and jumps in the sea water level time series? What would happen with projected sea level rise? Is the estimated return period affected? Should this affect the results and its confidence? are fair ones and perfectly justified. The non-stationary context is not covered by this paper because it moves us further away from the main objective which is the use and the confrontation of different methods for quantifying the exceedance probability of extreme sea levels. It could however be the object of another paper."

Minor comments

Comment	**Response to reviewer**
The abstract would benefit from being more explicit: describe the three methods used and highlight some of the main differences (with numbers) and implications from these methods.	Two sentences are now added to the abstract (lines 17-22 and 24-26)
The extensive use of brackets makes the text at times hard to follow.	Fixed
At the beginning of the results section, the authors present the R packages they used. In my opinion, this should belong to the Methods section.	the R packages we used are now presented in the Methods section
Page 1 – line 11: "Tide and extreme SSs are considered as independent". Is this an assumption you made for this research or based on your results? If this is an assumption, then it seems contradictory to want to study the dependence but already assume that it is independent.	It is rather an assumption for the Havre based on results.
Page 1 – line 18: "It has also been suggested that the questions of coincidence and dependency are essential for a combined tide and SS hazard analysis." I would think that this is the question this paper is trying to answer.	This sentence is now removed and replaced by the following one in the abstract just before talking about the case study: Lines 21-22: "The question we are trying to answer in this paper is then the coincidence and dependency essential for a combined tide and SS hazard analysis."
Page 2 – line 53: "that the probability of failure (The probability of exceeding an extreme event)": Written in this	"(The probability of exceeding an extreme event)" is now removed from the sentence.

way, it implies that the probability of failure is the equal to the exceedance probability and this is incorrect.	
Page 2 – line 65: "SSS": At this point in the text, this acronym has not been defined yet.	Fixed
Page 2 – line 71: "Salvadori and De Mechele". Please correct this typo for "Salvadori and De Michele"	OK
Page3–line111:" On the other hand, it is commonly known today that the tidal signals can be predicted". Did the authors want to put the emphasis on the accuracy of the tidal predictions? Because the use of "today" implies that this is recent while this is actually known for some decades.	The word "today" is now removed.
Page 4 – line 124: I think there is a mistake in equation 2 because fz(z) appears on both side of the equation. If I understood correctly, it should only be on the left-hand side of the equation	Right. The equation is now fixed.
Page4–line38-39: "Indeed, a SSS occurring with a high tide is more likely to induce a high sea level than an instantaneous SS occurring with any other tide." This statement is not clear to me. Can the authors elaborate to make their point?	This sentence is now simplified and replaced by the following one: Line 178: "Indeed, a SSS occurring with a high tide is likely to induce a high sea level"
Page 5 – line 150: "This feature makes the MSS a variable particularly useful for carrying out a PFHA exploring the entire tidal signal, not only the high tide ". If my understanding of the method is correct, each MSS value per tidal cycle is paired with the high tide value within this tidal cycle. If the MSS does not occur randomly within the tidal period, I believe this might highly overestimate your extreme sea levels which may not be useful for PFHA.	Yes indeed, if the MSS does not occur randomly within the tidal period. As mentioned earlier in our response to a general comments, the probability of coincidence would make it possible to conclude if the MSSs occur randomly in a tide cycle or not and it must be tested for many coastal systems (with different physical properties). On the other hand, overestimating extremes allow us to be more conservative in the nuclear safety field. But it is not our objective to overestimate the extreme sea levels. The following sentence (added to the conclusion section in response to a comment of another reviewer) takes up this view of point: Lines 385-390: "Indeed, since MSS is always greater than or equal to SSS and since the convolution process using MSS selects the maximum value of instantaneous SSs every tidal cycle, the RLs are systematically higher when the joint MSS-tide method is used. But without properly tackling the probability of coincidence concept (i.e. the chance that a maximum SS occurs at the same time with high tide) concept and the issue of temporal lag between tidal peaks and surge peaks, the results will be probably always overestimated, which may not be useful for PFHA."
Page 5 – line 157: "As it can also be noticed for this reference procedure, the variable of interest would be the maximum sea level between 2 high-tide values. " Why do the authors mention "between 2 high-tide values"? Did you sample using a peaks over threshold method with some independence window criteria or using GEV?	We extract the max sea level in each tidal cycle and then we use these data as raw data to extract extreme values with a classic POT frequency model.
Page 6 – line 187: please mention the final threshold selected, the resulting number of peaks used to fit the distribution in each case and add in supplementary the supplementary graphs.	The following sentence (with a table and a figure showing the POT frequency model characteristics) is

	now added at the end of the first paragraph of section results. Lines 238-240: "The POT model characteristics (threshold and associated average number of events per year) are presented in Table 2. The stability graphs for threshold selection are presented in Figure 5".
Page 6 – line 193: "storm surge RLs": shouldn't this be water level return levels?	Yes, it would be better. Changed.
Page 6 – line 197: "with the delta method". Please briefly explain what is the delta method and add appropriate references. I believe this is important since the authors go on to compare the width of the confidence interval.	The following sentence, with the appropriate reference, is now added to the end of the paragraph before the last one of the section results. Lines 251-253: "It is interesting to note that the delta method (*Ver Hoef, 2012*) is a classic technique in statistics for computing confidence intervals for functions of maximum-likelihood estimates. The variance of RL estimates are calculated using an asymptotic approximation to the normal distribution."
Page6–line218: "However, it should be noticed that extreme levels such as the MSSs may be only very weakly dependent." Can the authors elaborate on this sentence? I don't see why this would or would not be the case.	Because only one value per tidal cycle is extracted.
Page 7 – line 222: "This assumption is the most critical one since sea levels are highly non-stationary (due to the tide). " Shouldn't "tide" be replace with "storm surge" here?	Yes, indeed. Fixed.

Point-by-Point response / reviewer # 2

<table>
<tr><th>Comment</th><th>Responses to comments</th></tr>
<tr><td colspan="2">Abstract:</td></tr>
<tr><td>‘Tide and extreme SSs are considered as independent?’ This sentence is disconnected from the previous one. What do you mean exactly? The previous study assumes the independence between SSs and tides? I don’t understand the authors would study the dependence while they assume that “Tide and extreme SSs are considered as independent”.</td><td>It was assumed in the present paper that the tide and storm surge are independent <u>in an extreme value context</u> and a convolution model has been applied with a simple sum of them in the indirect method (with both, skew storm surges and maximum instantaneous ones).

Indeed, the general goal of the present paper is to characterize the hazard “coastal flooding” by combining the high-tide and extreme storm surges (SSSs & MSSs). A dependence analysis was conducted despite the fact that the study aims to use only the extreme values of these variables. Scatter graphs and the Spearman’s Rho have been used to measure the statistical dependence between high-tide and extreme SSs. It was concluded that this dependence is weak and sufficiently low to consider the variables of interest dependents.

The following sentence is now used:

In the Abstract, as suggested by one of the reviewers, the sentence “Tide and extreme SSs are considered as independent” in the abstract is now replaced by: Lines 11-12: “Most existing studies are generally based on the assumption that high-tides and extreme SSs are independent.”

In addition, In the Methods section:

Lines 147-148: “Indeed, as mentioned in the introductory section and as it will be discussed later in this paper, extreme levels such as MSSs may be only very weakly dependent with high-tides.”

The discussion section (lines 291-293 and 302-308 with figure 7) has been changed to add a discussion on the dependence analysis.

Another kind of dependence that caught our attention (but more important for the coincidence model) is the one between the high-tide and the other instantaneous storm surges around the high-tide (±6 hours). The Spearman’s Rho was used as a measure of this statistical dependence. A further discussion about this issue section is now added to the paper.</td></tr>
<tr><td>General comment 2: In the introduction, the authors discuss at length different types of other hazards happening in coastal areas (pluvial, fluvial floods) but this is not further looked into in the paper. If I understood correctly, the present study is on extreme sea levels and therefore extensively discussing about pluvial and fluvial floods seems out of the scope in my opinion. Similarly, it was not clear to me why the authors present in Table 1 the rainfall datasets if this is not used in this study.</td><td>We agree that discussing other flooding sources was a bit exaggerated. A part of this discussion is now removed.

Rainfall data characteristics are likewise removed from table 1.</td></tr>
<tr><td>in line 11 ‘Tide density? ‘ What do you mean by tide density</td><td>The tide is not distributed randomly and its density can be used instead of a distribution function.</td></tr>
<tr><td>The abstract does not reflect the main results of the work!!</td><td>The main results of the work are now presented in the abstract (24-26)</td></tr>
</table>

Introduction	
A very long sentence, difficult to understand! 'This goal is in line with the recent literature (e.g. Idier et al., 2012) challenging the use of the SSS and clearly demonstrates the importance of conducting extreme value analyses with maximum instantaneous ones. In order to achieve this goal, a third fitting procedure to estimate extreme sea levels using the maximum SS (MSS) between two consecutive 100 tides is introduced with an application so that it can be compared with the two first procedures.'	I admit that the two sentences must be better expressed. Lines 126-128: "This goal is in line with the recent literature (e.g. Idier et al., 2012) challenging the use of the SSS and clearly demonstrates the importance of using the maximum instantaneous surges (MSSs) instead." and, Lines 128-130: "In order to achieve this goal, a third fitting procedure to estimate extreme sea levels using the MSSs between two consecutive tides is introduced with an application so that it can be compared with the two first procedures."
It would be better if the choice of the Le Havre station can be justified: may be for the important interaction of the different driven forces induced by fluvial, tidal and wave activity.	The following sentence is now added (the last of the introduction): Lines 139-140: "One of the most important features of this case study is the fact that the lower parts of Le Havre city are likely to be flooded by coastal floods and that the region has experienced important storms during the last few decades."
Methods:	
What's MSS? What's JPM? It would be better if you can introduce clearly this!!	Thank you for this comment. MSS is the maximum instantaneous storm surge between two high tides and JPM is the joint probability method (a convolution between tide density and the surge distribution function). These definitions are proposed in the introductory section.
Also, I have not understood how do you determine the SSs from the instantaneous measurements? The total sea level provided by tides is the sum of the SLR component, the long-term geological component, tides and the residual; Do you have considered the long-term components?	May be the reviewer means how do you determine the MSSs from the instantaneous measurements? AS defined in the introductory section, MSS is the maximum hourly storm surge in each tidal cycle. But if the reviewer means the skew storm surge (SSS), it is the difference between maximum observed level and maximum predicted level in each tidal cycle. It is defined in the introductory section as follows: Lines 89-90: "It is the difference between the highest observed level and the highest predicted one, for a same high tide. These maximum levels can occur at slightly different times." As it is a difference between two total levels, this definition takes only the water rise du the meteorological conditions.
Also, another important issue can be raised here. We can consider that the residual part as the surges, which is the dominant component sure but it's not the only one for this case Le Havre where the stochastic signal contains both surges and the fluvial effects! May be this should be signaled in the methods and the discussion.	The following sentence is now added to the method section. Lines 166-168: "It should also be noted that for the case Le Havre the residual part as the surges is not the only one and despite the fact that it is the dominant component, the stochastic signal also contains the fluvial effects."
Again, I raise the necessity for readers, not expert if this area, to have the full description of the different abbreviations used!!! So, it will be better to introduce at the beginning of use each term!	A description of the different abbreviations used is now provided.
In relation with the use of the time series of LE Havre, how do you process the gaps?	In the calculation of the effective duration, we take into account: – The declustering tool used in independent events extract takes into account the presence of the gaps.

	– The presence of gaps is also considered in the settings of the POT frequency model. Indeed, after threshold selection, the effective duration of observations (in years) is calculated by subtracting the gaps periods: the effective duration is then the ratio between number of days with observations and the average number of days in a year (365.25)
How do you have determined surges? By harmonic analyses?	The surges time series were already available. They were calculated in another framework.
Line 150 of page 5: “This feature makes the MSS a variable particularly useful for carrying out a PFHA exploring the entire tidal signal, not only the high tide”. MSS value is paired with the high tide value within each tidal cycle? Then, the MSS could not occur always randomly within the tidal period. This approach could overestimate the extreme levels, I think.	Yes indeed, it could overestimate the extreme levels if the MSS does not occur randomly within the tidal period. The probability of coincidence would make it possible to conclude if the MSSs occur randomly in a tide cycle or not and it must be tested for many coastal systems (with different physical properties). On the other hand, overestimating extremes, if it occurs, allows us to be more conservative in the nuclear safety field. But it is not our objective to overestimate the extreme sea levels.
line 157: As suggested, the variable of interest would be the maximum sea level between 2 high-tide values. So, my doubts is the following: Did you sample by the use of POT with the consideration of some independence window criteria or by the use of GEV?	The POT frequency model has been used after a declustering step.
Results Lines 253-251: variables are missing!	Ok. It’s now fixed.
Page 6: what‘s the final threshold selected and the peak number used to fit the distribution in each case	These settings are now presented in table 2 (and figure 5).
Page 6 (line 193) the use of ‘storm surge RLs’ , do you refer to be water return levels?	Yes. Changed.
Page 6 (line 197) the delta method. Please can you explain what ‘s this?	The following sentence, with the appropriate reference, is now added to the end of the paragraph before the last one of the section results: Lines 251-253: “It is interesting to note that the delta method (*Ver Hoef, 2012*) is a classic technique in statistics for computing confidence intervals for functions of maximum-likelihood estimates. The variance of RL estimates are calculated using an asymptotic approximation to the normal distribution.”
The results section should be more detailed, may some illustrations are required in this stage!	More results and discussion are now presented in the paper.

Point-by-Point response / reviewer # 3

Specific comments

Comment 1- State of the art.	**Our response**
I agree with the authors that most studies assume that "Tide and extreme SSs are considered as independent" (as stated in the abstract). Yet, this is not so systematic: I would reformulate by highlighting: "Most existing studies are generally based on the assumption that tide and extreme SSs are independent."	Ok. The sentence is now changed. It is now replaced by the following one. Lines 11-12: "Most existing studies are generally based on the assumption that high-tides and extreme SSs are independent."
Some studies (not cited by the authors) have addressed this problem with different approaches. These should be underlined in the introduction and further discussed by the authors. In particular, - Coles, S., & Tawn, J. (2005). Seasonal effects of extreme surges. Stochastic Environmental Research and Risk Assessment, 19(6), 417-427; - Gouldby, B., Méndez, F. J., Guanche, Y., Rueda, A., & Mínguez, R. (2014). A methodology for deriving extreme nearshore sea conditions for structural design and flood risk analysis. Coastal Engineering, 88, 15-26. – see section 3.2; - Pirazzoli, P. A., & Tomasin, A. (2007). Estimation of return periods for extreme sea levels: a simplified empirical correction of the joint probabilities method with examples from the French Atlantic coast and three ports in the southwest of the UK. Ocean Dynamics, 57(2), 91-107; Note that a more recent overview on the interaction with tides is provided by Idier et al. (2019): Idier, D., Bertin, X., Thompson, P., & Pickering, M. D. (2019). Interactions between mean sea level, tide, surge, waves and flooding: mechanisms and contributions to sea level variations at the coast. Surveys in Geophysics, 40(6), 1603-1630.	We agree that adding more references would enrich the state of the art. This paragraph is now added to introductory section: Lines 64-81: "The problem of the surge-tide interactions has been addressed in the literature for many regions and with different approaches (Coles and Tawn, 2005; Gouldby et al., 2014; Pirazzoli, 2007; Idier et al., 2012; Idier et al., 2019). It was shown that tide–surge interactions can be relevant in several regions. The tide–surge interactions at the Bay of Bengal (corresponding to the effect of the tide on atmospheric surge and vice versa) were analyzed by Johns et al., (1985) and Krien et al., (2017). They showed that tide–surge interactions in shallow areas of this large deltaic zone are in the range ±0.6m occurred at a maximum of 1 to 2 hours after low tide. Similar results were obtained by Johns et al. (1985), Antony and Unnikrishnan (2013) and more recently Hussain and Tajima (2017). Focusing on the English channel, Idier et al. (2012) used shallow water model to make surge computations with and without tide for two selected events (November 2007 North Sea and March 2008 Atlantic storms). The authors concluded that the instantaneous tide–surge interaction are significant in the eastern half of the English Channel, reaching values of 74 cm in the Dover Strait, which is about half of maximal storm surges induced by the same events. They also concluded that Skew surges are tide-dependent, with negligible values (less than 5 cm) over a large portion of the English Channel, but reaching several tens of centimeters in some locations such as the Isle of Wight and Dover Strait. More recently, Idier et al. (2019) have investigated the interactions between the sea level components (sea level rise, tides, storm surges, etc.) and the tide effect on atmospheric storm surges is among the main interactions investigated in their review. The authors stated that the studies, and other ones, converge to highlight that tide–surge interactions can produce tens of centimeters of water level at the coast." The following references are now added to the references list: • Antony, C. and Unnikrishnan A.S.: Observed characteristics of tide–surge interaction along the east coast of India and the head of Bay of Bengal. Estuar. Coast. Shelf. Sci. 131, 6–11. doi: 10.1016/j.ecss.2013.08.004, 2013. • Coles, S., Tawn, J.: Seasonal effects of extreme surges. Stoch Environ Res Ris Assess, 19, 417–427, doi: 10.1007/s00477-005-0008-3, 2005. • Gouldby, B., Mendez, F., Guanche, Y., Rueda, A. and Mínguez, R.: A methodology for deriving extreme nearshore sea conditions for structural design and flood risk analysis. Coastal

	Engineering. 88, 15–26. doi: 10.1016/j.coastaleng.2014.01.012, 2014. • Hussain M.A. and Tajima Y.: Numerical investigation of surge–tide interactions in the Bay of Bengal along the Bangladesh coast. Nat Hazards 86(2):669–694. Doi: 10.1007/s11069-016-2711-4, 2017. • Krien Y, Testut L, Islam AKMS, Bertin X, Durand F, Mayet C, Tazkia AR, Becker M, Calmant S, Papa F, Ballu V, Shum CK, Khan ZH Towards improved storm surge models in the northern Bay of Bengal. Cont. Shelf Res. 135, 58–73, doi: 10.1016/j.csr.2017.01.014, 2017. • Pirazzoli, P.A. and Tomasin, A.: Estimation of return periods for extreme sea levels: a simplified empirical correction of the joint probabilities method with examples from the French Atlantic coast and three ports in the southwest of the UK. Ocean Dynamics, 57(2), 91-107, 2007. • Idier D, Dumas F, Muller H Tide–surge interaction in the English channel. Nat Hazard Earth Sys, 12, 3709–3718, doi : 10.5194/nhess -12-3709-2012, 2012. • Idier, D., Bertin, X., Thompson, P. and Pickering, M.D.: Interactions Between Mean Sea Level, Tide, Surge, Waves and Flooding: Mechanisms and Contributions to Sea Level Variations at the Coast. Surv Geophys 40, 1603–1630, doi: 10.1007/s10712-019-09549-5, 2019.
Finally, the beginning of the introduction is mainly focused on the problem of NPPs though the problem of tide-surge dependence is of interest in all applications of the domain of coastal engineering. The authors should maybe either reformulate the introduction to be more general, or reflect the focus on NPPs directly in the title.	The first paragraph of the introduction is now modified to be more general and consider other coastal facilities.
2. Details on the implementation.	
The manuscript would benefit from additional implementation details (and figures) on the different steps of the proposed method. In particular, - Figure on the time-series of Le Havre with examples of MSS (SSS) and High tide sampling; - An empirical bivariate scatterplot High Tide versus MSS (or SSS); - Consider the possibility of statistical methods to estimate tideâ˘ A˘Rsurge interaction like the analysis by Feng et al. (2015): Figure 6 or the chiâ˘ A˘Rsquare test described by Haigh et al., (2010); - Stability graphs for the choice of the threshold values; - Error estimates on the GPD parameters (line 206); - Further details on the delta method (page 6, line 197).	Many figures (time series, scatter plots, stability plots for threshold selection, etc.) are now added. - To the case study section: Figure 4. Studied time-series of Le Havre: (top) predicted and observed sea levels; (middle) SSSs data and (bottom) the MSSs. - To the discussion section**:** Figure 7. Analysis of the dependence between the tide and the SSSs, the MSSs and the ESL events. - To the results section: Figure 5. Stability plots for threshold selection: (top) SSSs, (middle) MSSs and (bottom) ESL.
Besides, the authors refer to R packages: these references should be preferably located in the method section, together with additional formal details on the corresponding methods.	Ok. Done.
At the end of the discussion (page 7, from lines 340), the authors highlight some interesting alternative methods. These are very relevant and	It is now clarified in a further discussion section.

I must admit that after reading them, I wonder why the authors did not consider them in the frist place. Could the authors clarify this aspect?	
3. Application.	
The application cases consists of one tide gauge, where the interaction between tide and surge is known to be high. Though the results on this site is useful to highlight	It is a good idea. This is a thesis paper and only Le Havre case study was used in this thesis.

Minor comments:

Comment	Response to reviewer
- Page 2 (line 65): “SSS” has not been introduced before.	Ok. Fixed.
- Page 2 (line 71): “Salvadori and De Mechele” should be “Salvadori and De Michele”	Ok. Fixed.
- Page 6 (line 193): “storm surge RLs”: sea level RLs? -	OK. Done.
Page 7 (line 255): the symbol after “this temporal difference” is not depicted properly in the manuscript pdf. The problem also appears in line 258 and 260.	OK. Fixed.

Point-by-Point response / reviewer # 4

Major comments:

<table>
<tr><th>Comment 1- Introduction/State of the art</th><th>Our response</th></tr>
<tr><td>Although the article mentions some key references that investigated the issue of combining tides and SSs (e.g. Tawn and Vassie (1989), Dixon and Tawn (1994), Haigh et al (2010), Kergadallan et al (2014)), it is not clear how the present work differs from or compares with others, for example what is not addressed in those studies that will be in the present work.

The authors also could have cited Mazas et al(2014)“Applying POT methods to the Revised Joint Probability Method for determining extreme sea levels”, Coast. Eng. 91, 140-150. This study is in line with what is done in the present work. Mazas et al (2014) compared several methods to determine extreme sea levels on a single case study (Brest) using convolution of the tide and surge density functions, but testing hourly vs skew surges and two methods for handling tide-surge interaction. They also compared results with a direct approach, just as authors did. I think the paper would benefit replacing the present work in this context and showing the novelty with respect to previous research.</td><td>This is an interesting comment.

• The work of Mazas et al. (2014) is now cited in the introduction section with a brief comparison to the present work.
• More details and references about the tide-surge dependence are now added to the introduction section.
• More details about the work performed by Kergadallan et al., (2014) and how it differs from the present work is now added to the introduction section.
• The fact that Idier et al. (2012) and Kergadallan et al., (2014) performed the work with skew surges (and not the MSSs) is a main point of difference with the present work. The following sentence was already in the introduction:

Lines 126-128: “This goal is in line with the recent literature (e.g. Idier et al., 2012, Kergadallan et al., 2014) challenging the use of the SSS and clearly demonstrates the importance of using the maximum instantaneous surge (MSS) instead.”

We agree that adding more references would enrich the state of the art. These two paragraphs are now added to introductory section:

1. Lines 130-135: “Mazas et al., (2014) proposed a review of tide-surge interaction methods and applied a POT frequency model (with the GPD and Poisson distribution functions) to the family of JPM-type approaches for determining extreme sea level values in a single case study (Brest). The authors focused on the use of a mixture model for the surge component, which allows probabilities to be quantified for the entire range of sea level values, not just for the extreme ones, which is not the case here in the present paper.”
2. Lines 64-81: “The problem of the surge-tide interactions has been addressed in the literature for many regions and with different approaches (Coles and Tawn, 2005; Gouldby et al., 2014; Pirazzoli, 2007; Idier et al., 2012; Idier et al., 2019). It was shown that tide–surge interactions can be relevant in several regions. The tide–surge interactions at the Bay of Bengal (corresponding to the effect of the tide on atmospheric surge and vice versa) were analyzed by Johns et al., (1985) and Krien et al., (2017). They showed that tide–surge interactions in shallow areas of this large deltaic zone are in the range ±0.6m occurred at a maximum of 1 to 2 hours after low tide. Similar results were obtained by Johns et al. (1985), Antony and Unnikrishnan (2013) and more recently Hussain and Tajima (2017). Focusing on the English channel, Idier et al. (2012) used shallow water model to make surge computations with and without tide for two selected events (November 2007 North Sea and March 2008 Atlantic storms). The authors concluded that the instantaneous tide–surge interaction are significant in the eastern half of the English Channel, reaching values of 74 cm in the Dover Strait, which is about half of maximal storm surges induced by the same events.</td></tr>
</table>

	They also concluded that Skew surges are tide-dependent, with negligible values (less than 5 cm) over a large portion of the English Channel, but reaching several tens of centimeters in some locations such as the Isle of Wight and Dover Strait. More recently, Idier et al. (2019) have investigated the interactions between the sea level components (sea level rise, tides, storm surges, etc.) and the tide effect on atmospheric storm surges is among the main interactions investigated in their review. The authors stated that the studies, and other ones, converge to highlight that tide–surge interactions can produce tens of centimeters of water level at the coast."
As the article focuses on extreme sea levels and indirect approach for EVA of sea levels,I think the entire introduction section should be revised to better document previous research in that domain (see for example the article of Batstone et al (2013)).	As mentioned in the previous point, the introduction section has been revised and research in the combined tide-surge field and EVA are better documented. The following references are now used in the introduction section and added to the references list. • Antony, C. and Unnikrishnan A.S.: Observed characteristics of tide–surge interaction along the east coast of India and the head of Bay of Bengal. Estuar. Coast. Shelf. Sci. 131, 6–11. doi: 10.1016/j.ecss.2013.08.004, 2013. • Coles, S., Tawn, J.: Seasonal effects of extreme surges. Stoch Environ Res Ris Assess, 19, 417–427, doi: 10.1007/s00477-005-0008-3, 2005. • Gouldby, B., Mendez, F., Guanche, Y., Rueda, A. and Mínguez, R.: A methodology for deriving extreme nearshore sea conditions for structural design and flood risk analysis. Coastal Engineering. 88, 15–26. doi: 10.1016/j.coastaleng.2014.01.012, 2014. • Hussain M.A. and Tajima Y.: Numerical investigation of surge–tide interactions in the Bay of Bengal along the Bangladesh coast. Nat Hazards 86(2):669–694. Doi: 10.1007/s11069-016-2711-4, 2017. • Krien Y, Testut L, Islam AKMS, Bertin X, Durand F, Mayet C, Tazkia AR, Becker M, Calmant S, Papa F, Ballu V, Shum CK, Khan ZH Towards improved storm surge models in the northern Bay of Bengal. Cont. Shelf Res. 135, 58–73, doi: 10.1016/j.csr.2017.01.014, 2017. • Pirazzoli, P.A. and Tomasin, A.: Estimation of return periods for extreme sea levels: a simplified empirical correction of the joint probabilities method with examples from the French Atlantic coast and three ports in the southwest of the UK. Ocean Dynamics, 57(2), 91-107, 2007. • Idier D, Dumas F, Muller H Tide–surge interaction in the English channel. Nat Hazard Earth Sys, 12, 3709–3718, doi : 10.5194/nhess -12-3709-2012, 2012. • Idier, D., Bertin, X., Thompson, P. and Pickering, M.D.: Interactions Between Mean Sea Level, Tide, Surge, Waves and Flooding: Mechanisms and Contributions to Sea Level Variations at the Coast. Surv Geophys 40, 1603–1630, doi: 10.1007/s10712-019-09549-5, 2019. • Mazas, F., Kergadallan, X., Garat, P. and Hamm L.: Applying POT methods to the Revised Joint Probability Method for determining extreme sea levels. Coastal Engineering 91 140–150, 2014.
2. Methods:	

This section must be completed, as some basic information on EVA are not even mentioned. For instance, the authors do not describe the sampling method used in the analysis (either for SS or for total sea level marginals): do they use POT (as indicated in the results section line 187)? What extreme laws are used (Generalised Pareto Distribution or Generalised Extreme Value distribution?)? At least, the formula of the CDF should be provided, with appropriate definitions of parameters.	A sampling method sub-section is now added to the methods section (lines 198-206): **"2.4 The sampling method** The Peaks-Over-Threshold (POT) sampling method is used conduct the frequency analyses in the present work. Commonly considered as an alternative to the annual maxima method, the POT method models the peaks exceeding a relatively high threshold. The distribution of these peaks converge to the Generalized Pareto Distribution (GPD) theoretical distribution. In addition, the threshold leads to a sample more representative of extreme events. However, the threshold selection is subjective and an optimal threshold is difficult to obtain. Indeed, a too low threshold can introduce a bias in the estimation because some observations may not be extreme data and this violates the principle of the extreme value theory. On another hand, the use of a too high threshold reduces the sample size. " In addition, the section results contains now figures and more details about the frequency model settings (lines 236-240 with Table 2 and Figure 5).
I think that beginning of section 4 (results) from line 180 to line 195 should be included in the methods section.	Ok. It is now in the methods section.
The method chosen by the authors for the indirect approach is a convolution of densities (tide and SS). But it is not clear to me if the tide density uses only high water values or the entire hourly time series. In addition, nothing is said about the derivation of tide density (which method is used? What is the duration of the sample used to derive the density?)	All the tide density is used in the model but only the high tide is summed to SSSs and MSSs in order to calculate extreme sea levels. On the other hand, we used predicted tides already available for the Havre harbour, with the same duration of the sea level data set. Studied time-series of Le Havre (observed and predicted tide, SSSs and MSSs) are now better presented in the case study section (with plots).
Nothing is said either on the modelling of coincidence of storm surges and high tides in the methods section, although this is the title of the article.	A further discussion section take up all these aspects is now added to the paper (lines 309-369).
3. Case study and data:	
Data characteristics (such as time step for the time series) should be given in the text (in addition to Table 1).	As mentioned in table 1, the time step is one hour. The word "hourly" is now added in the case study section (line 227): "The 1971-2015 observed and predicted <u>hourly</u> sea levels … "
The authors state that Le Havre is prone to marine and pluvial floods. In addition, Table 1 relates characteristics of pluvial time series. Logically, I expected to see some compound events in the following with an appropriate method to tackle the issue. As pluvial data are not used in the present work, they should not be mentioned at all.	It was a mistake. Pluvial data is now removed from the table 1.
There is a problem in the time span of tide gauge time series: 1971-2015 in the text VS 1938-2017 in Table 1.	You are right. The time span of tide gauge time series is now fixed.
Results:	

The authors write "the POT threshold selection process has been adapted to meet this criterion and the thresholds are, even though, checked regarding the stability graphs of the GPD parameters estimated with the maximum likelihood method." To appreciate the quality of the fit and to justify their choices, the authors should provide some plots.	Stability plots for threshold selection are now presented in the results section and discussed (lines 236-240 with Table 2 and Figure 5).
As mentioned above, I am not sure if the convolution process uses only high water values for the tide density. If this is the case (it should be according to Figure 2), and since MSS is always greater than or equal to SSS, it is logical that return levels (RLs) of method3 are always higher than those obtained with method 2. Method3 is actually conservative as it selects the maximum value of instantaneous SS every 12 hours (or so). But without properly tackling the issue of temporal lag between tidal peaks and surge peaks, the results are probably overestimated. The authors should discuss this point.	Yes indeed, the approach using the MSS variable could overestimate the extreme levels if the MSSs does not occur randomly within the tidal period. The probability of coincidence (considering time lag between tidal and surge peaks) would make it possible to conclude if the MSSs occur randomly in a tide cycle or not and it must be tested for many coastal systems (with different physical properties). On the other hand, overestimating extremes, if it occurs, allows us to be more conservative in the nuclear safety field. But it is not our objective to overestimate the extreme sea levels. The following paragraph is now added to the discussion section (first paragraph): Lines 310-314: "As shown in Figure 6, RLs obtained with the joint M tide method are always higher than those using SSS. This is consistent the fact that the convolution process based on MSS uses only high w values for the tide density (as it selects the maximum value of instantane SSs every 12 hours) and since MSS is always greater than or equal to S It is then logical to consider that the joint MSS-tide method is m conservative than the SSS based one.." And in the conclusion as well: Lines 385-389: "Indeed, since MSS is always greater than or equal to SSS and since the convolution process using MSS selects the maximum value of instantaneous SSs every tidal cycle, the RLs are systematically higher when the joint MSS-tide method is used. But without properly tackling the probability of coincidence concept (i.e. the chance that a maximum SS occurs at the same time with high tide) concept and the issue of temporal lag between tidal peaks and surge peaks, the results will be probably always overestimated."
There is a problem in the presentation of results: Table 2 and Figure 4 are not consistent. If I trust Table 2, then the reference curve (method 1) is the middle one. This is consistent with the text of the article (line 233). But still, I find the behavior of the RL curves in Figure 4 odd especially at lower return periods. For instance, according to previous research (see e.g. Kergadallan et al, 2014 or Mazas et al, 2014), method 2 should provide higher return levels than method 1. The results section would be improved with plots of return levels of SS (for both SSS and MSS).	Yes indeed, there is a mistake in the legend. It is now fixed.
Discussion:	
The authors write in line 244 "A copula-based approach may be used to study the dependence of instantaneous SSs (or sea levels)." What exactly does that mean? Is it a dependence in time (to model autocorrelation)? Copula would	Here, we are rather talking about dependence between variables. The sentence is now changed to: Lines 297-298: "A copula-based approach may be used to consider this dependence."

be used to model time dependence of SS? To take into account time dependence of SS or sea levels, extremal index could be considered (see e.g. Batstone et al, 2013).	
The paragraph in lines 248-252 is exactly what we expect to be presented in the article. The authors then propose a method to tackle the issue of coincidence but they do not try it. However, this should be the core of the article.	A further discussion section presenting the coincidence between SSs and high tide is now added to the paper.
I have some doubts about the proposed method. Although Δs is a random variable, it is not an extreme variable. Expressed in hours, it is bounded between 0 and 12 (or -6 and6) and can take any value with in this interval. There is no tail of the distribution and I do not think extreme value theory can apply in that case. Thus, speaking of return level of Δs does not make sense. In fact, I would say a uniform distribution would be a good fit for Δs.	Very good issue! Yes indeed, non-extreme distributions could be more appropriate for the lag time variable. The following sentence is now added in the further discussion section. Lines 250-253: "Indeed, Δs is expressed in hours and it is not an extreme variable, it is bounded between -6 and 6H and can take any value with in this interval. There is then no tail of the distribution and the extreme value theory is not the appropriate framework to model this random variable. Thus, a uniform distribution would be a good fit for Δs." The RLs term is removed and the sentence is now changed to: Lines 354-355: "Use the desired probability to weight the probabilities of the MSSs, assuming that MSSs and Δs are independent. Many scenarios using many of Δs probabilities can be used in a probabilistic framework."
The statement in lines 260-261 is wrong. A frequency analysis does not imply an extreme value analysis.	Ok.

Minor comments:

Comment 1- Introduction/State of the art	Our response
L11: Authors write that "Tide and extreme SS are considered as independent." I think what authors mean is that in general, in most studies, tide and extreme SS are considered as independent. So this sentence should be modified as numerous studies have tried to tackle the issue of tide-surge dependence.	Ok. Done.
L33: word to be deleted (in bold): "The safety demonstration and protections and are..."	Ok. The word "are" is now deleted.
L46-47: Probabilistic Flood Hazard Assessment. At least, the authors should mention the issue of multivariate return periods. Assessing flood hazard does not imply necessarily to compute the probabilities that one or more parameters are exceeded (see e.g. Salvadori et al (2011) "On the return period and design in a multivariate framework, Hydrol. Earth Sys. Sci., 15, 3293-3305).	Thank you for this comment. It is interesting. The following sentence is now added (but at a later paragraph in the introduction section). Lines 91-94: "As more than one explanatory variable are often used in a PFHA and in case these variables are dependent, the dependency structure must be modeled and a consistent theoretical framework must be introduced for the calculation of the return periods and design quantiles with multivariate analysis based on Copulas (e.g. Salvadori et al., 2011). Indeed,…" Also, the following reference is now added to the references list: "Salvadori, G., De Michele, C., and Durante, F.: On the return period and design in a multivariate

	framework, Hydrol. Earth Syst. Sci., 15, 3293–3305, https://doi.org/10.5194/hess-15-3293-2011, 2011."
L51: "a river nuclear sites". Fragment unclear, consider revising.	Ok. Replaced by: "… flood hazard for nuclear sites located alongside rivers…" (line 58).
L53: spelling mistake (in bold) : "It is a common belief today that" .	Ok. Corrected.
The probability of failure is not systematically the probability of exceeding an extreme event. This statement should be modified accordingly.	Changed.
L59 : "volume" does not seem appropriate for a river flood. I suggest to use the word "flow".	The sentence is already deleted as suggested by another reviewer.
L62: word is missing (in bold): "...marine flooding which is a combination of the tide (which can be predicted) with a SS."	Ok. Corrected.
Defined like this, SS must also include the effect of waves (setup, runup). Since the effect of waves on total water level is not discussed nor mentioned in the article, this sentence needs rephrasing.	The following sentence is now added two sentences later: Line 86: "It should be noted that the effect of waves (runup and setup) on total water level is not discussed in the present paper."
L65: acronym SSS is not defined before.	Ok. It is now defined.
L71: Spelling mistake (in bold): "According to Salvadori and De Michele (2004)..."	Ok. Fixed.
L80: Spelling mistake (inbold): Haigh et al (2010). Also the use of the word "recently" for a 10-year-old study is questionable.	Yes, sorry about that. Fixed.
L87: I think a final point is missing after "distribution function of SSs".	Right! A final point is now added.
L91: reword (in bold): "GEV model is recommended"	Ok. Corrected.
L92: the authors write "Based on the regional observations, the process of estimation of extreme water levels..." Does that mean that this method (method1) uses a regional frequency analysis ?	No, here we talk about the FEMA study which recommend working in a regional scale… with regional frequency analysis. Otherwise, in reply to the question: all the methods use at-site observations.
L108: The authors write "Indeed, the SS is the main driver of coastal flood events". This is not true everywhere nor always. Coastal floods can occur from three main mechanisms: overflowing, overtopping, breaching. Impacts of waves on structures are sometimes crucial and the main driver of coastal flooding. The statement must be reworded. -	We then suggest: "Indeed, the SS is one of the main driver of coastal flood events". (line 84)
L111: The authors state again (also in the introductory section) that "tidal signals and SSs are independent". This is not true, as shown in previous research (Idier et al, 2012; Batstone et al, 2013). The sentence must be reworded.	Replaced with: Lines 147-148: "Indeed, as mentioned in the introductory section and as it will be discussed later in this paper, extreme levels such as MSSs may be only very weakly dependent with high-tides."
L115-116 : the wording is awkward as extreme sea level is proposed as a variable to represent SS. This must be reworded.	The sentence is now changed to: Lines (152-153): "So the question that arises here is which variable of interest can be used to better characterize coastal flooging?"
L124: Equation (2) is false: fZ(z) on the right hand side must be deleted.	Ok. Corrected.

L126-127: I think there is a confusion here. The tide signal is clearly not a stationary stochastic process, but SS can be considered as so. As the authors write the opposite, they should clarify this point.	You are right, there is a confusion here. The sentence is now changed to: Lines 164-166: "The hourly SS is often considered as a stationary stochastic process, since meteorological and seasonal effects give rise to series of SSs randomly distributed in time, but this is not the case of the hourly theoretical tide signals."
L157-158: The sentence is not clear, I do not understand what is the variable of interest. Rewording should be considered.	The sentence is now changed to: Lines (196-197): "The maximum sea level between 2 high-tide values is the variable of interest used for this reference procedure."
L174: Sentence is awkward and needs rephrasing.	Sentence changed to: Lines (229-230): "One of the most important features of Le Havre is the fact that it is subject to marine submersions and instabilities"
L193: Wording mistake (in bold): "and 1000-year sea level RLs".	OK. Corrected.
L205-206: it seems that GPD is used to describe the tails of the distributions of SS. This does not seem consistent with statement in L91 where GEV is recommended. The authors should clarify this point.	The GEV was recommended by FEMA (2004)… but the GPD is used herein. It is now clarified in the Introduction section. (Line 120)
L210-226: I find this paragraph unclear, I do not see what the authors want to say. I suggest making it clearer.	The paragraph is now modified and we hope that it is clearer now.
L231-232: I think there is a wording mistake (in bold): "The difference is high for high return periods."	You are right. Corrected.
L233: I think there is a wording mistake (in bold): "The difference is significant for lower return periods"	Ok. Corrected.
L236-239: I do not understand the end of the paragraph. The authors should clarify their statement.	Ok. The statement is now modified and we hope it is clearer now.
L257: POT is not an fitting method, it is a sampling method.	Ok. But The sentence is already changed.
L262: The authors write "figure 4 shows that extreme sea level events tend to occur at the time of the high tide". I do not see that in Figure 4. The authors should clarify their thought and better explain this result.	The sentence is: "Furthermore, figure 4 shows that extreme sea level events (the right tail of the distribution: the middle curve) tend to occur at the time of the high tide, as expected." The paragraph is now removed to a further discussion section and the sentence is now replaced by: Lines 314-315: "As expected, figure 4 shows that ESL events at the right tail of the distribution, represented by the middle curve, tend to be close to high SSS RLs which are dominated by the high-tide."

L266-267: The end of section 5 is awkward and should be reworded. It seems that to overcome the problem of method 2, one just needs to follow Tawn and Vassie (1989). Then a question arises: why is method 3 necessary if method 2 limitation can be solved?	This is a good comment. The sentence is now changed to: Lines 318-320: "To overcome this problem, one can use the joint tide-MSS convolution method. Another solution is to use an empirical method to define the left tail of the distribution and an extreme values analysis for the right tail as stated by Tawn and Vassie (1989)."
L269-270: The first statement of the Conclusions section is a bit exaggerated. The authors should reword it.	The first sentence is now replaced by the following: Lines 371-372: "In the present paper, we provided a reasoning for the need, in a PFHA framework, to combine flood phenomena to better characterize coastal flooding hazard."
L277: I am not sure acronym ESL has been defined before.	It was defined in the introduction section. I also define it in the abstract.
L281: spelling mistake (in bold): "Fitting results in terms of probability..."	Ok.
L290: word missing (in bold)?: "...around the high tide (high tide +/- 3 hours).	Ok.
References should be listed alphabetically and homogenized.	Ok.
Figure 2: SSS is defined as the difference between maximum observed minus predicted sea levels. Therefore, it is a discretized time series and not a continuous one as pictured in Fig 2.	The figure 2 is now changed.
Overall, English could be improved.	I hope English is now better.

Modelling dependence and coincidence of storm surges and ~~high tide~~high-tide: Methodology and simplified case study in Le Havre (France)

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Abstract. Coastal facilities such as nuclear power plants (NPPs) have to be designed to withstand extreme weather conditions and must, in particular, be protected against coastal floods because it is the most important source of coastal lowlands inundations. Indeed, considering the combination of tide and extreme storm surges (SSs) is a key issue in the evaluation of the risk associated to coastal flooding hazard. Most existing studies are generally based on the assumption that high-tides and extreme SSs are independent. ~~Tide and extreme SSs are considered as independent.~~ While there are several approaches to analyze and characterize coastal flooding hazard with either extreme SSs or sea levels, only few studies propose and compare several approaches combining the tide density with the SS variable. Thus this study aims to develop a method for modelling dependence and coincidence of SSs and ~~high tide~~high-tide. In this work, we have used existing methods for tide and SS combination and tried to improve the results by proposing a new alternative approach while showing the limitations and advantages of each method. Indeed, in order to estimate extreme sea levels, the classic joint probability method (JPM) is used by making use of a convolution between tide and the skew storm surge (SSS). Another statistical indirect analysis using the maximum instantaneous storm surge (MSS) is proposed in this paper as an alternative to the first method with the SSS variable. A direct frequency analysis using the extreme total sea level is also used as a reference method. The question we are trying to answer in this paper is then the coincidence and dependency essential for a combined tide and SS hazard analysis. The city of Le Havre in France was used as a case study. Overall, the example has shown that the return levels (RLs) estimates using the MSS variable ~~different combinations~~ are quite different from those obtained with of the method using the SSSs, with acceptable ~~.~~ uncertainty. Furthermore, the shape parameter is negative form all the methods with a much heavier tail when the SSS and the extreme sea levels (ESLs) are used as variables of interest.

~~It has also been suggested that the questions of coincidence and dependency are essential for a combined tide and SS hazard analysis.~~

Key-words: Coastal flooding, Combination, Joint Probability Method, Convolution, Dependence, Coincidence

1. Introduction

~~More than 80% of electricity in France is derived from nuclear energy.~~ Like any other urban facilities, Nuclear Power Plants (NPPs) can be subject to external influences and aggressions such as extreme environmental events (river and/or marine flooding, heat spells, etc.). Both nuclear and urban facilities have to be designed to withstand extreme weather conditions. ~~Five NPPs are located on the Atlantic coast (including the Channel).~~ During the last few decades, France has experienced several violent storms (the great storm of 1987, Lothar and Martin cyclone in

1999, Klaus in 2009 and Xynthia in 2010, for instance) that gave rise to exceptional SSs. ~~The Blayais NPP~~Many coastal facilities was partially or completely flooded when storm Martin struck the French coast in 1999. A combination of an exceptional SS, of a ~~high tide~~high-tide and high waves ~~(~~induced by strong winds~~)~~ led to the overflow of ~~the~~ many dikes which~~.~~ ~~According to Mattéi et al. (2001), the dikes~~ were not designed for such a concomitance of events. In the nuclear safety field for instance, ~~A~~ a guide to protection, including some fundamental changes in the assessment of flood risks, has therefore been produced by the Nuclear Safety Authority (ASN, 2013). However, to be conservative, approaches used in the guide are deterministic which do not take into account all the local specificities of each site. The safety demonstration and protections ~~and~~ are periodically reviewed to ensure compliance with the increased safety requirements. The present work could be used to enrich safety verification approaches, by proposing other approaches and confronting them to the reference method currently used in the guide. To supplement knowledge which can be acquired from the deterministic method, the probabilistic approach has been identified as an effective tool for assessing risk associated with hazards as well as for estimating uncertainties.

The first probabilistic study in the nuclear safety field was conducted in the United States in 1975 (US-NRC, 1975). This report focused on estimating the probability of occurrence of meltdown accidents with associated radiological consequences. Currently, probabilistic approaches are applied in several fields such as medicine, chemical industry, insurance and aeronautics. Many studies have already been conducted for the seismic hazard (IAEA, 1993; Beauval, 2003; Gupta, 2007), the tsunami hazard (IRSN, 2015), and other climatic hazards such as tornadoes (US-NRC, 2007). There are not many probabilistic studies yet in the fields of climate and hydrometeorology, as it is an approach barely used. In fact, very few researches and developments are explicitly referred by their authors as conclusive and operational. Probabilistic Flood Hazard Assessment (PFHA) is identified by Bensi and Kanney (2015) as a first step in a Probabilistic Risk Assessment (PRA). According to the authors, it is an evaluation of the probabilities that one or more parameters representing the severity of the external flood (water level, duration, and associated effects) are exceeded in a site of interest. Also, the authors discuss the j~~J~~oint p~~P~~robability m~~M~~ethod (JPM) as an alternative to existing deterministic and statistical methods such as the Empirical Simulation Technique (EST). Kügel (2013) proposed a methodology for characterizing the external flood hazard ~~in the case of a river~~for nuclear sites located alongside rivers and the articulation of this Hazard study with a flooding Probabilistic Safety Assessment (PSA).

It is a common belief~~ve~~ today that the probability of failure, ~~(The probability of exceeding an extreme event)~~ over an infrastructure lifetime is one of the most important pieces of information an engineer can communicate. The estimation of the~~is~~ probability of exceeding an extreme event should be based on the combination of all flood ~~phenomena~~ sources (e.g. Pluvial, fluvial and ~~marine~~ coastal floods) which are most often dependent because they are induced by the same storm. ~~For example, extreme SSs are often accompanied by rains in coastal areas.~~ Mostly, a flood phenomenon can be characterized by several explanatory variables, some of which are correlated. The problem of the surge-tide interactions has been addressed in the literature for many regions and with different approaches (Coles and Tawn, 2005; Gouldby et al., 2014; Pirazzoli, 2007; Idier et al., 2012; Idier et al., 2019). It was shown that tide–surge interactions can be relevant in several regions. The tide–surge interactions at the Bay of Bengal (corresponding to the effect of the tide on atmospheric surge and vice versa) were analyzed by Johns et al., (1985) and Krien et al., (2017). They showed that tide–surge interactions in shallow areas of this large deltaic zone are in the range ±0.6m occurred at a maximum of 1 to 2 hours after low tide. Similar results were obtained by Johns et al. (1985), Antony and Unnikrishnan (2013) and more recently Hussain and Tajima (2017). Focusing on the

English channel, Idier et al. (2012) used shallow water model to make surge computations with and without tide for two selected events (November 2007 North Sea and March 2008 Atlantic storms). The authors concluded that the instantaneous tide–surge interaction are significant in the eastern half of the English Channel, reaching values of 74 cm in the Dover Strait, which is about half of maximal storm surges induced by the same events. They also concluded that Skew surges are tide-dependent, with negligible values (less than 5 cm) over a large portion of the English Channel, but reaching several tens of centimeters in some locations such as the Isle of Wight and Dover Strait. More recently, Idier et al. (2019) have investigated the interactions between the sea level components (sea level rise, tides, storm surges, etc.) and the tide effect on atmospheric storm surges is among the main interactions investigated in their review. The authors stated that the studies, and other ones, converge to highlight that tide–surge interactions can produce tens of centimeters of water level at the coast.

~~For example, river floods can be described not only by its peak, but also by other characteristics such as its volume and duration. An intense rainfall event is characterized by its intensity and its duration, the correlation of which is not usually negligible.~~ On the other hand, there are some phenomena which are described by other explanatory phenomena. The case of multi-components phenomena, that will receive our attention in the present paper, is the ~~marine~~ coastal flooding which is a combination of the tide, ~~(which can be predicted)~~ with a SS.~~.~~ Indeed, the SS is one of the main drivers of coastal floods~~ events~~. It is an abnormal rise of water generated by a storm (low atmospheric pressure and strong winds), over and above the predicted tide. It should be noted that the effect of waves (runup and setup) on total water level is not discussed in the present paper. Extreme storms can produce high sea levels, especially when they coincide with ~~high tide~~high-tide. The skew storm surge SSS is a sea level component which is often considered as the fundamental input or ~~(~~the quantity of interest~~)~~ for statistical investigations of coastal hazards. It is the difference between the highest observed level and the highest predicted one, for a same ~~high tide~~high-tide. These maximum levels can occur at slightly different times.

As more than one explanatory variable are often used in a PFHA and in case these variables are dependent, the dependency structure must be modeled and a consistent theoretical framework must be introduced for the calculation of the return periods and design quantiles with multivariate analysis based on Copulas (e.g. Salvadori et al., 2011). Indeed, ~~Numerous~~ numerous studies have shown that, in case of multivariate hazards, a univariate frequency analysis does not allow to estimate in a complete way the probability of occurrence of an extreme event (Chebana and Ouarda, 2011; Hamdi et al., 2016). According to Salvadori and De Mi~~e~~chele (2004), modelling the dependency allows a better understanding of the hazard and avoids under/over-estimating the risk. Unsurprisingly, some ideas have been proposed in the literature for combining tides and SSs and to help address such an important issue. JPM is an indirect method that made an improvement in addressing the main limitations of the direct methods (e.g. the annual maxima method (AMM) and the r-largest method (RLM)) (Haigh et al., 2010). Several studies refer to the JPM for the probabilistic characterization of storms (Batstone et al., 2013; Haigh et al., 2010; Pugh and Vassie, 1978; USACE, 2015). Tawn and Vassie (1989) proposed a Revised JPM (RJPM) in which the distribution of surges is composed by a left tail defined by an empirical method and a right tail defined by frequency analysis. Dixon and Tawn (1994) made some modifications on the Revised JPM ~~the RJPM~~ and proposed a new model to take into account the interaction between instantaneous SS and tide. Recently, Haigh et~~and~~ al. (2010) showed the advantages of indirect methods (i.e. JPM, Revised JPM~~RJPM~~) compared to direct ones (i.e. AMM and RLM). More recently, Kergadallan et al. (2014) proposed an extension of the ~~undertook~~ the model proposed by ~~ethod of~~ Dixon and Tawn (1994) using skew storm surges (SSSs) at 19 French harbours along the Atlantic and English Channel coasts of France. ~~to compare several methods.~~ The authors have used two different approaches (the seasonal dependence and the interaction between SSs and tides) to study the dependence of the SSs on the tides with three methods (the seasonal approach, Dixon and Tawn (1994) model and the revisited Dixon and Tawn model). It was concluded that the interaction between SSSs and high-tides affect more significantly the results than the seasonal dependence for more than one-half of the harbours.

Some other studies have been proposed in the literature to tackle the PFHA. The most important contribution proposes two methods. The first estimates extreme sea levels (ESLs) with the JPM (Pugh and Vassie, 1980). Indeed, this approach combines separated frequency distributions for the tide (usually deterministic and exact) and the SS (frequency analysis based on the extreme value theory). It is a calculation of the convolution based on the tidal levels density function and of a distribution function of SSs. (Duluc et al., 2012) have shown that the quality of the results from this convolution approach for small return periods is questionable. The second procedure uses the data of observed maximum water levels (Chen et al., 2014; Haigh et al., 2014; Huang et al., 2008). This approach was recommended by FEMA's guideline (FEMA, 2004) for coastal flood mapping, in which~~. The~~ the GEV model ~~was~~ is recommended to conduct the frequency analysis of extreme water levels, if long-term datasets are available. Based on the regional observations, the process of estimation of extreme water levels uses an adequate frequency analysis model to estimate the distribution parameters, the desired return levels (RLs) and associated confidence intervals.

Overall, our goal is to build on the approaches and developments proposed in the literature and revive the debate as to how researchers and engineers can combine tide with SS to estimate extreme sea levels. This goal is in line with the recent literature (e.g. Idier et al., 2012, Kergadallan et al., 2014) challenging the use of the SSS and clearly demonstrates the importance of ~~conducting extreme value analyses with~~using the maximum instantaneous ~~ones~~surge (MSS) instead. In order to achieve this goal, a third fitting procedure to estimate extreme sea levels using the ~~maximum SS (~~MSS~~)~~ between two consecutive ~~tide~~high-tides is introduced with an application so that it can be compared with the two first procedures. Mazas et al., (2014) proposed a review of tide-surge interaction methods and applied a POT frequency model (with the GPD and Poisson distribution functions) to the family of JPM-type approaches for determining extreme sea level values in a single case study (Brest). The authors focused on the use of a mixture model for the surge component, which allows probabilities to be quantified for the entire range of sea level values, not just for the extreme ones, which is not the case here in the present paper.

The paper is organized as follows. The section 2 takes up the two fitting procedures proposed in the literature (the JPM with a convolution between tides and SSSs and the frequency analysis directly on sea levels) and proposes a new one based on the convolution between tides and MSSs. In section 3, the fitting procedures are applied on the observed and predicted sea levels at the Le Havre tide gauge in France used as a case study. One of the most important features of this case study is the fact that the lower parts of Le Havre city are likely to be flooded by coastal floods and that the region has experienced important storms during the last few decades. ~~Some theoretical basis for the multivariate analysis using copulas will be addressed~~

2. Methods

Tide and SSs are usually the subject of a statistical study to determine the probability of exceeding the water level cumulating the two phenomena. Indeed, the SS is the main driver of coastal flood events. It is an abnormal rise of water generated by a storm, over and above the predicted tide. ~~Unlike to what is done very often in the literature, the question of dependency is not essential at all to combine phenomena in the present work.~~ As it would be analyzed later in the discussion section, the dependency, in an extreme value context, is analyzed but not considered to combine the phenomena in the present work. Indeed, as mentioned in the introductory section and as it will be discussed later in this paper, ~~tidal signals and SSs are independent.~~ extreme levels such as MSSs and high-tides may be only very weakly dependent.

On the other hand, it is commonly known ~~today~~ that the tidal signals can be predicted, and are not aleatory like the SSs. What is somewhat odd in the present work is that one thus seeks to combine a distribution function of ~~(~~random variable~~phenomenon)~~ with a density of tide which is ~~(~~deterministic~~)~~. In order to estimate extreme sea levels, a JPM is used by making use of a convolution between tide and SSs. So the question that arises here is which variable of interest ~~represents the SSs~~can be used to better characterize coastal flooding? Three variables are then proposed: (i) the SSS; (ii) the MSS and (iii) the extreme sea level. The theoretical basis for the fitting procedures using these variables is addressed in the following subsections.

Relative to some chosen datum, each hourly observed sea level $Z(t)$, may be considered as the sum of its tide $X(t)$ and storm surge component $Y(t)$, i.e.:

$$Z(t) = X(t) + Y(t) \tag{1}$$

Thus if the probability density functions of the tidal and surge components are $f_X(x)$ and $f_Y(y)$ respectively then the probability density function $f(z)$ of z, under the assumption that the tide and surge components are independent, is:

$$f_Z(z) = \int_{-\infty}^{+\infty} f_X(x) \times f_Y(z-x)\, dx \tag{2}$$

As it can be seen in equation 2, the dependence on time, t, is omitted when replacing $X(t)$ by X, $Y(t)$ by Y, and $Z(t)$ by Z. This implies a stationarity assumption for the involved time series. The hourly SS ~~theoretical tide signal~~ is often considered as a stationary stochastic process, since meteorological and seasonal effects give rise to series of SSs randomly distributed in time, but this is not the case of the hourly theoretical tide signals. ~~SSs since SS meteorological and seasonal effects give rise to series of SSs not randomly distributed in time~~.

It should also be noted that for the case Le Havre the residual part as the surges is not the only one and despite the fact that it is the dominant component, the stochastic signal also contains the fluvial effects.

2.1 Joint SSS - tide probabilistic method

This method is based on the decomposition of the sea level into a sum of two contributions: the tide which is evaluated theoretically and the aleatory component SS ~~(aleatory component)~~ obtained by subtracting the predicted tide from the observed sea level. Extreme storms can produce high sea levels, especially when it occurs simultaneously with ~~high tide~~high-tide. The SSS is a sea level component which is often considered as the fundamental input for statistical investigations of coastal hazards. It is defined as the difference ~~calculated~~ between two observed and predicted maximums ~~(observed-predicted)~~ and is not impacted by the shift of the two signals which may be biased (see figure 1). As shown in the left panel of figure 2, the SSS is defined herein as the difference between the highest observed level and the highest predicted one, for a same ~~high tide~~high-tide (see equations 1 and 2). Further noteworthy features of SSSs are its occurrence with a ~~high tide~~high-tide. Indeed, a SSS occurring with a ~~high tide~~high-tide is ~~more~~ likely to induce a high sea level ~~than an instantaneous SS occurring with any other tide~~. Thus, for safety requirements, SSS is the most often used in the literature Kergadallan et al. (2014).

Still, even if this procedure uses the suitable variable of interest, it has its limitations. Indeed, it is not uncommon that the MSS, which can occur randomly somewhere between two consecutive tides, is greater than the SSS. Widening the window around the ~~high tide~~high-tide, in which extreme SSs are extracted, could improve frequency estimation of extreme sea levels. When this window is maximum (12 hours, for instance), the variable of interest naturally becomes the MSS. Moreover, it was demonstrated in the literature that the tide and SSS interaction at ~~high tide~~high-tide cannot be neglected (Kergadallan et al., 2014).

2.2 Joint MSS - tide probabilistic method

The right panel of figure 2 illustrates the case of an instantaneous SS signal, the variables would be the MSS and the ~~high tide~~high-tide M_n. As mentioned in the previous section, the MSS can occur randomly somewhere in a tide cycle. One of the most important features of MSS is that it is more informative than the SSS. Indeed, the MSS covers the whole instantaneous SS signal. This feature makes the MSS a variable particularly useful for carrying out a PFHA exploring the entire tidal signal, not only the ~~high tide~~high-tide.

2.3 Inference with the ESL: the reference method

For comparison purposes, we also analyzed sea levels signals for which we focused our attention on the frequency analysis on extreme sea levels without decomposing them into tides and surges. This yields to direct statistics and estimates of the RLs without combining tides and surges. The intent of this analysis is only to illustrate and obtain results that can serve as a reference for the comparison of the joint probability procedures. ~~As it can also be noticed for this reference procedure, the~~ The maximum sea level between 2 high-tide values is the variable of interest used for this reference procedure. ~~would be~~is ~~the maximum sea level between 2 high-tide values~~.

2.4 The sampling method

The Peaks-Over-Threshold (POT) sampling method is used conduct the frequency analyses in the present work. Commonly considered as an alternative to the annual maxima method, the POT method models the peaks exceeding a relatively high threshold. The distribution of these peaks converge to the Generalized Pareto Distribution (GPD) theoretical distribution. In addition, the threshold leads to a sample more representative of extreme events (Coles, 2001). However, the threshold selection is subjective and an optimal threshold is difficult to obtain. Indeed, a too low threshold can introduce a bias in the estimation because some observations may not be extreme data and this violates the principle of the extreme value theory. On another hand, the use of a too high threshold reduces the sample size (Hamdi et al., 2014).

On the other hand, all the simulations were carried out within the R environment (open source software for statistical computing: http://www.r-project.org/). The SeaLev library, developed by the French Institute for Radiological Protection and Nuclear Safety (IRSN), was used for the standard approach involving the convolution of the probability density functions of the tidal and surge heights to obtain the distribution of total sea levels. The frequency analyses were performed with the Renext library also developed by IRSN (IRSN and Alpstat, 2013). The Renext package was specifically developed for flood frequency analyses using the Peaks-Over-Threshold (POT) method.

3 Case study and data

The city of Le Havre is an urban city in the Seine-Maritime department, on the English Channel coast in Normandy (France). It is a major French city located in northwestern France. A map showing the location of the Le Havre city in France can be found in figure 3. The name Le Havre means "the harbour" or "the port". The port of Le Havre is, moreover, among the largest in France. For these reasons, the city of Le Havre remains deeply influenced by its maritime traditions.

Due to its location on the coast of the Channel, the climate of Le Havre is temperate oceanic. Days without wind are rare. There are maritime influences throughout the year. According to the meteorological records, precipitation is distributed throughout the year, with a maximum in autumn and winter. The months of June and July are marked by some relatively extreme storms on average 2 days per month. One of the characteristics of the region is the high variability of the temperature, even during the day. The prevailing winds are from north-northeast for breezes and, from the southwest sector for strong winds.

The joint tide-surge probability and the frequency analysis of extreme sea levels are performed on the city of Le Havre. The 1971-2015 observed and predicted hourly sea levels recorded at the port of Le Havre were provided by the French Oceanographic Service (SHOM - Service Hydrographique et Océanographique de la Marine). Figure 4 shows the sea level time series of Le Havre, as well as the studied extreme SSs (SSSs and MSSs). One of the most important features of ~~the~~ Le Havre ~~(as a case study)~~ is the fact that ~~Le Havre is a city~~it is subject to marine submersions and instabilities of coastal cliffs (Elineau et al., 2013; Elineau et al., 2010; Maspataud et al., 2016). In particular, the lower part of the city (Saint-François district, for instance) is likely to be flooded by marine and pluvial floods. Data characteristics are shown in the table 1. These data were first processed to keep only common periods containing a minimum of gaps. The choice of the variables to be probabilized is done at this stage.

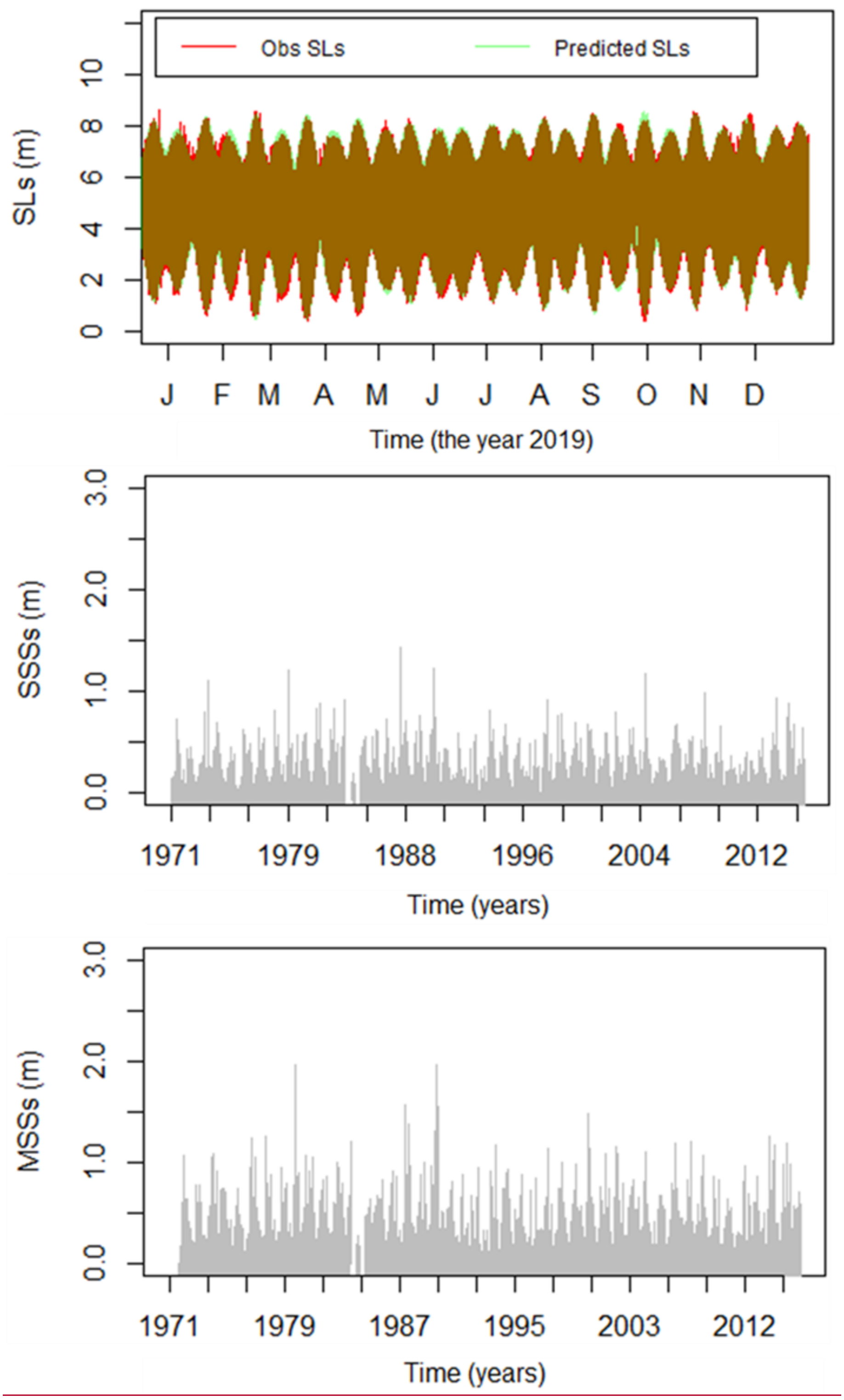


Figure 4: Studied time-series of Le Havre: (top) predicted and observed sea levels; (middle) SSSs data and (bottom) the MSSs.

4. Results

~~All the simulations were carried out within the R environment (open source software for statistical computing: http://www.r-project.org/). The SeaLev library (developed by the French Institute for Radiological Protection and Nuclear Safety - IRSN) was used for the standard approach involving the convolution of the probability density functions of the tidal and surge heights to obtain the distribution of total sea levels. It is the same package that was used by Duluc et al., (2012). The frequency analyses were performed with the Renext library also developed by IRSN (IRSN and Alpstat, 2013). The Renext package was specifically developed for flood frequency analyses using the Peaks-Over-Threshold (POT) method.~~

Since we need to get comparable annual rates of extreme sea level events, the POT threshold selection process has been adapted to meet this criterion and the thresholds are, even though, checked regarding the stability graphs of the GPD parameters estimated with the maximum likelihood method~~.~~ The POT model characteristics (threshold and associated average number of events per year) are presented in Table 2. The stability graphs for threshold selection are presented in Figure 5.

Table 2: POT thresholds for SSS, MSS and ESL variables

	SSS	MSS	ESL
Threshold u (m)	0.59	0.75	0.81
Poisson intensity λ (average N^{br} of events/year)	1.45	1.13	2.83

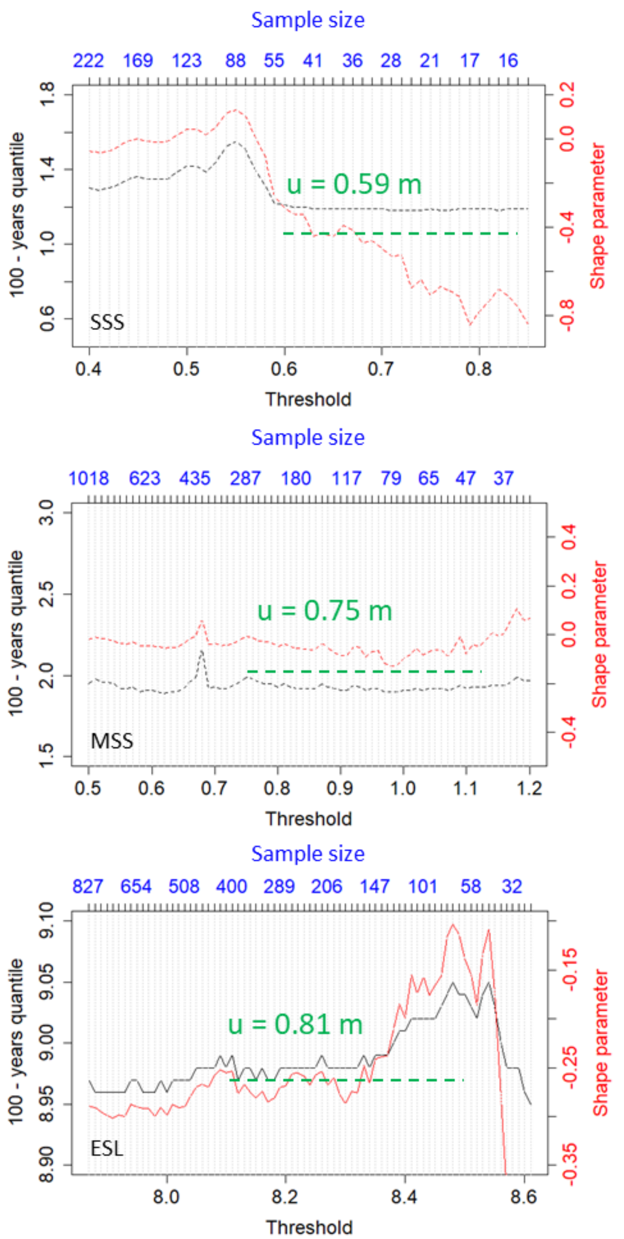


Figure 5: Stability plots for threshold selection: (top) SSSs, (middle) MSSs and (bottom) ESL

The main results of the joint surge-tide probability method, ~~(~~with the SSS and MSS based fitting procedures~~)~~, and the results of the direct frequency analysis of the extreme sea levels ~~(3rd procedure)~~ as well, with all the diagnostics are presented in terms of RL plots, estimates of the quantiles of interest and associated 95% confidence intervals. In these results, the main focus was set to the 10-, 50-, 100- and 1000-year ~~storm surge~~sea level RLs. Prior to the application of the JPM, the SSSs and MSSs are calculated first from observed and predicted sea levels. The results of the application on the Le Havre are summarized in table 3~~2~~ and presented in figure 6~~4~~.

The RL estimates obtained with the MSS based convolution are quite different from those of the one based on SSSs. The results of the calculation of confidence intervals (with the delta method) are presented with transparent polygons in figure 6~~4~~ and in table 3~~2~~ as well. As it can be noticed, the confidence intervals are relatively narrow. Indeed, the relative width of the~~se~~ intervals around the 1000-year RL obtained with reference method, did not exceed 12%

~~(around the 1000-year RL obtained with reference method)~~. Better yet, the confidence intervals are narrower when using the joint probability procedures. It is interesting to note that the delta method (Ver Hoef, 2012) is a classic technique in statistics for computing confidence intervals for functions of maximum-likelihood estimates. The variance of RL estimates are calculated using an asymptotic approximation to the normal distribution.

Furthermore, it can be seen in figure 6~~4~~ that for a given RL, the return period given by the MSSs-based procedure is much lower than that given by the one based on the SSSs. The RLs are thus more frequently (i.e. on average 10 times more frequently) exceeded randomly in a tidal cycle (i.e. as the MSS can occur randomly somewhere inside a tidal cycle) than at the ~~high tide~~high-tide moment (i.e. if we suppose that SSS often occurs at the ~~high tide~~high-tide moment).

It is noteworthy that the shape parameter ξ of the General Pareto Distribution (GPD) is negative for all the cases (i.e. $\xi = -0.2$; $\xi = -0.07$ and $\xi = -0.12$ for the SSS, MSS and ESL based fitting procedures, respectively). This parameter governs the tail behavior of the GPD. The right tail of the distribution is much heavier for the procedures using SSSs and the ESLs than for the one using MSSs.

5 Discussion

To objectively evaluate the merits and shortcomings of each of the methods described in section 2, the associated assumptions ~~made in developing them~~ must be analyzed first. The JPM is developed under the assumption of independence between the tidal signal and ~~both S~~SSs. ~~and MSS on one side and independence of extreme hourly sea levels on the other side.~~ Tawn and Vassie (1989) found that this ~~e latest~~ assumption was false. Considering that ~~the tide and the surge are independent is an~~this assumption ~~that~~ may be true under certain circumstances as proved by William et al. (2016) for the largest mid-latitude storm surges and the corresponding tide. A tendency to overestimate sea levels, ~~because of~~due to the fact that the correlation between tide ~~in the hourly~~ SSs has been ignored, was recognized in the literature (Pugh and Vassie, 1978, 1980; Walden et al., 1982). However, it should be noticed that extreme levels such as the MSSs may be only very weakly dependent with high-tides. This constitutes a distinctive feature and advantage of the MSS based fitting procedure introduced in the present paper. It is a major point of differentiation between the joint surge-tide probability procedures described in sections 2. Furthermore, the hourly theoretical tides are in utmost cases considered as a realization of stationary ~~stochastic~~ process. This assumption is the most critical one since sea levels are highly non-stationary ~~(~~due to the ~~tide~~storm surge~~)~~. As previously argued to overcome this limitation, the variability arises from the SSs ~~(since SS meteorological and seasonal effects lead to SS series which are not randomly distributed in time and as most high tides are similar in term of their value)~~ which can be considered as stationary over the storms season for instance. For this argument to be less subjective, most ~~high tide~~high-tides are similar in term of their value and must be lower than the SS variation in extreme events.

The question one can ask is how to improve the modelling in such a way that the bias between the procedures using SSSs and MSSs and the reference one is reduced as far as possible? Indeed, as depicted in figure 6~~4~~, the second procedure overestimates extreme sea levels for all the return periods (a maximizing envelope). The RLs estimates for MSS based procedure are about 50 to 60 cm higher than those obtained when the SSS are used. The difference between the upper and middle curves increase as the return period goes up. The difference is high for ~~the low~~ high return periods. Inversely, the difference between the lower and middle curves increase as the return period goes down. The difference is significant for ~~the major~~lower return periods. It is noteworthy that the middle curve is supposed to represent the RLs of reference. An objective answer to our question cannot in any case suggest a modification in the reference method. Two methodological issues could provide us with solutions and answers to the question. First, the dependence structure that exists between the high-tide and the extreme ~~instantaneous~~ SSs around the ~~high tide~~high-tide could be modelled. Extreme SSs one hour before the ~~high tide~~high-tide, at the time of the high-tide and one hour after can be used. A larger window can likewise be used to consider the SSs around the high-tide in a multivariate context.

A visual inspection with the scatter graphs and the Spearman's Rho numerical criteria have been used to measure the statistical dependence between storm surges and tide at the moment of the high-tide and around it (±1 hour). This is useful when modeling the coincidence of the high-tide with extreme storm surges, for instance. The Multivariate frequency analysis consists in studying the dependence structure of two or more variables through a function that depends on their marginal ~~(univariate)~~ distribution functions. The multivariate theory is based on the mathematical concept of copula (Sklar, 1959), which allows linking the distributions of the variables according to their degree of dependence. More details can be found in (Salvadori and De Michele, 2004; Nelsen, 2006). A copula-based approach may be used to ~~study~~ consider thise dependence ~~of instantaneous SSs (or sea levels)~~. In the case of a copula of sea levels, no convolution is needed. The convolution of ~~a copula~~ of SSs distribution with a density of tide permits to obtain a ~~copula~~ distribution of sea levels. This ~~first~~ latter solution is proposed herein as an alternative to the ~~first procedure fitting~~multivariate analysis using ~~the SSSs~~a copula.

The figure 7 shows the scatter graphs that provide a visual information about the dependence between the high-tide and the other variables (SSS, MSS and ESL). It can be concluded that the dependence with the two storm surge variables SSS and MSS is weak and sufficiently low to consider the variables statistically independents. This finding is supported by the Spearman's Rho coefficients presented in Table 4. The two sea level components (high-tide and extreme SSs) are then considered as independent random variables and the distribution of the total sea level can be determined by convolution. Otherwise, a multivariate analysis based on the use of the copulas theory can be used.

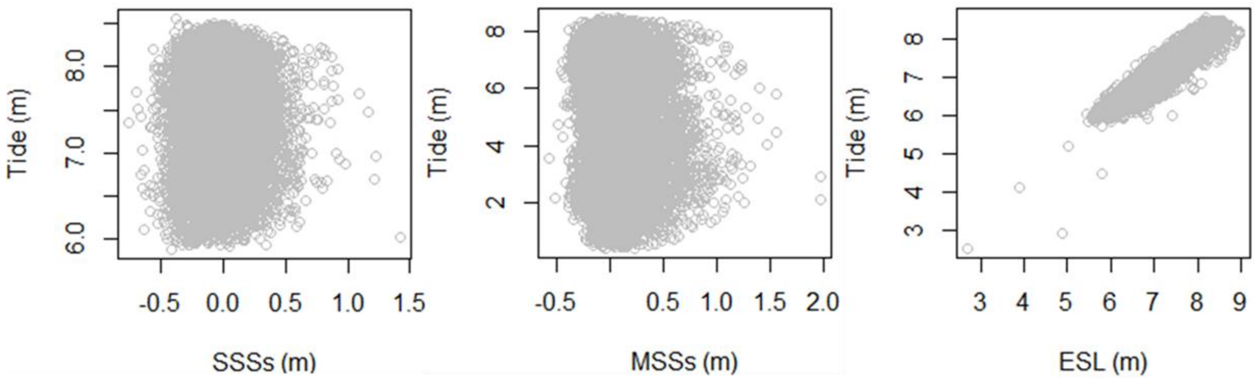


Figure 7: Analysis of the dependence between the tide and the SSSs, the MSSs and the ESL events

Table 4: Spearman's Rho coefficients as a measure of dependence between the tide and the other variables

	SSSs	MSSs	MaxSL
tide	-0.02	-0.06	0.96

6. Further discussion

As show in Figure 6, RLs obtained with the joint MSS-tide method are always higher than those using SSS. This is consistent with the fact that the convolution process based on MSS uses only high water values for the tide density (as it selects the maximum value of instantaneous SSs every 12 hours) and since MSS is always greater than or equal to SSS. It is then logical to consider that the joint MSS-tide method is more conservative than the SSS based one. As expected, figure 4 shows that ESL events at the right tail of the distribution, represented by the middle curve, tend to be close to high SSS RLs which are dominated by the high-tide. The results of this procedure confirm the general finding highlighted in the literature (Fortunato et al., 2016; High et al., 2016) that the return level estimations obtained with the convolution tide-SSS are not adapted up to a certain return period (100 years in the case of Le Havre). To overcome this problem, one can use the joint tide-MSS convolution method. Another solution is to use an empirical method to define the left tail of the distribution and an extreme values analysis for the right tail as stated by Tawn and Vassie (1989).

On the other hand, the current practices and statistical approaches to characterize the coastal flooding hazard by estimating extreme storm surges and sea levels still have some weaknesses. Indeed, the combination of the tide and the storm surge do not take into account several scenarios in particular those with a time-lag where the tide and the storm surge could give likewise extreme sea levels. The choice of variables (high-tide, SSSs, MSS, etc.) would be a decisive step and an integral part of the logic behind the idea of combining the two phenomena. Interestingly, these variables could also include other explanatory variables such as the time-lag between the two phenomena (tide and SS). This time-lag would be an additional variable and it is defined as the difference of time of occurrence of the second variable with respect to the first (e.g. time between a maximum storm surge and a high-tide).

6.1 coincidence probability concept

Our interest to the probability of coincidence comes from our belief that a bias is introduced with the joint-MSS convolution because it does not take into account the time difference between the maximum instantaneous SS and the high-tide. A probability of coincidence (i.e. the chance that a MSS occurs at the same time with high-tide) can be used to better characterize the extreme sea levels using the MSS. In the present paper, we are only interested in the concept of the coincidence probability and the statistical dependence between MSS and tide at the moment of the high-tide and around it (±6 hours). An appropriate coincidence probability concept would then allow to better estimate the probabilities and thus reduce the bias and bring the RLs closer to those obtained by the reference method.

Let Δ be the time-lag between the high-tide and the MSSs in each tide cycle. When considering coincidence, an additional hazard curve, associated to the variable Δ can be built. The time-lag variable Δ, which would allow us to compute a probability of coincidence, could be involved in a multivariate frequency analysis to consider the dependence structure between the variables. It is also interesting to note that the probability of coincidence would make it possible to conclude if the MSSs occur randomly in a tide cycle or not. The work must be performed for many coastal systems with different physical properties to conclude whether or not there is a systematic temporal dependence, and whether or not the extreme sea levels are overestimated if this is indeed the case.

~~Second.~~,

~~we believe that a bias is introduced with the MSS based procedure because it does not take into account the time difference between the maximum instantaneous SS and the high tide. A probability of coincidence (i.e. the chance that a MSS occurs at the same time with high tide) can be used to better characterize the extreme sea levels using the MSS. An appropriate coincidence probability concept would then allow to better estimate the probabilities and thus reduce the bias and bring the RLs closer to those obtained by the reference method.~~

As illustrated~~shown~~ in the right panel of figure 2 the MSS can occur randomly somewhere around the high-~~-~~tide M_n. The time difference between the MSS and the high-~~-~~tide is random as well. It is therefore quite legitimate to study it with a frequency analysis method ~~One can introduce an additional random variable to describe this temporal difference □~~. Then a coincidence probability concept can be drawn as follows:

- Extract an independent sample of Δ~~Δs~~
- Fit this sample with the ~~POT method~~appropriate distribution function. “Indeed, Δs is expressed in hours and it is not an extreme variable, it is bounded between -6H and 6H and can take any value with in this interval. There is then no tail of the distribution and the extreme value theory is not the appropriate framework to model this random variable. Thus, a uniform distribution would be a good fit for Δ.
- ~~Choose a RL of □ (100-year RL, for instance) and~~ U~~u~~se the desired~~its~~ probability to weight the probabilities of the MSSs, ~~(i.e.~~ assuming that MSSs and Δ_ ~~Δs~~ are independent~~)~~. Many scenarios using many of these probabilities can be used in a probabilistic approach.

~~It is noteworthy that □ is a random variable and therefore it is quite legitimate to study it with a frequency analysis method as the MSS~~.

~~Furthermore, figure 4 shows that extreme sea level events (the right tail of the distribution: the middle curve) tend to occur at the time of the high tide, as expected. The results of this procedure confirm the general finding highlighted in the literature (Duluc et al., 2012) that the return level estimations obtained with the convolution tide-SSS are not adapted up to a certain return period (100 years in the case of Le Havre). To overcome this problem, one can use an empirical method to define the left tail of the distribution and an extreme values analysis for the right tail as stated by Tawn and Vassie (1989).~~

On the other hand and focusing on the statistical dependence, extreme SSs samples around the high-tide (at the time Δ of the high-tide) was extracted. The largest window (±6 hour) centered on the time of the high-tide was used and the statistical dependence was then studied. Table 5 shows the Spearman’s Rho measuring the statistical dependence between storm surges and tide at the moment of the high-tide and around it (±3 hour). It can be easily concluded that the dependence between SSs and tides is very high around the time of high-tide and it becomes weaker as delta increases. As mentioned in the previous section, the dependence structure that exists between the MSSs around the high-tide could be modelled with copulas.

Table 5: Spearman's Rho calculated between high-tide and all the instantaneous surges in the tidal cycle

Δ	-6	-5	-4	-3	-2	-1	+1	+2	+3	+4	+5	+6
High-tide	0.29	0.28	0.21	0.41	0.61	0.85	0.77	0.60	0.56	0.44	0.33	0.30

6.2 The non-stationary context

It is noteworthy that the climate change in the past and working in a non-stationary context can greatly affect and invalidate the fit of the storm surge and sea level PDFs. Indeed, questions such as: what is the effect of potential trends and jumps in the sea water level time series? And should this affect the results and its confidence? are fair ones and perfectly justified. The non-stationary context is not covered by this paper because it moves us further away from the main objective which is the use and the confrontation of different methods for quantifying the exceedance probability of extreme sea levels. It could however be the object of another paper."

7~~6~~. Conclusions

In the present paper, we provided ~~detailed~~ a reasoning for the need, in a PFHA framework, to combine flood phenomena to better ~~avoid over or under estimations~~ characterize coastal flooding hazard~~of extreme water levels~~. Few ideas have been proposed in the literature to tackle the combination of tidal signals with extreme SSSs to estimate extreme sea levels. The present work supports these ideas, takes up the tidal signals and SSSs convolution procedure and proposes a new procedure based on the MSSs useful to exploit likewise the extreme SS events occurred during medium and low tide hours. Three fitting procedures have been investigated. The first one employs the SSS as an explanatory variable with the tidal signals which are combined with a JPM using a convolution of the tide density and the SSS distribution function. The second procedure uses the same technique except that the MSSs are used instead of the SSSs. In the third approach, a frequency analysis is performed using ESLs.

Another consideration in this paper was applying and illustrating these approaches on the example of the sea levels in Le Havre, northwestern France, over the period 1971–2015. It may be noted that the methodology is not exemplary developed for this case study; it applies to any site likely to experience a marine flooding.

Fitting results in terms of probability plots and extrapolated RLs using the three approaches are examined. Overall, the application has shown that the RL estimates for MSS based convolution are quite different from those corresponding to the SSS based one. ~~It has also been suggested that the questions of coincidence and dependency are essential for a combined tide and SS hazard analysis.~~ Indeed, ~~as shown in figure 4,~~ since MSS is always greater than or equal to SSS and since the convolution process using MSS selects the maximum value of instantaneous SSs every tidal cycle, the RLs are systematically higher when the joint MSS-tide method is used. But without properly tackling the probability of coincidence concept (i.e. the chance that a maximum SS occurs at the same time with high-tide) concept and the issue of temporal lag between tidal peaks and surge peaks, the results will be probably always overestimated. the results of the ~~second~~ MSS based ~~fitting~~ procedure are likely to contain a bias ~~(~~comparing to the direct statistics on ESLs~~)~~ which becomes more and more important as return periods increase. In order to reduce this bias, the coincidence probability concept~~ (i.e. defined in this paper as the chance that a maximum SS occurs at the same time with high tide)~~ could~~an~~ be helpful in making a more appropriate assessment of the risk ~~(associated to ESLs)~~ using the MSS. On the other hand and if the MSS based~~second~~ ~~procedure~~ convolution is to be used, the application has shown the utility of modelling the dependence structure that exists between the hourly SS values around the high~~-~~tide (~~high tide~~high-tide ± 6~~3~~ hours). Figure 6~~4~~ shows that ESL events at ~~(~~the upper tail of the distribution (the middle curve) tend to occur at the time of the ~~high tide~~high-tide, as expected. The results of this procedure confirm the general finding highlighted in the literature is that the RL estimations obtained with the convolution tide-SSS are not conclusive up to a certain return period (100 years in the case of Le Havre).

Perspective: An in-depth study could help to thoroughly improve the proposed procedure based on the use of MSS by developing the concept of coincidence and apply the developed concept on other sites of interest. A concept of coincidence and methodology to be developed should find additional applications for the assessment of risk associated to other combining flooding phenomena (e.g. pluvial flooding and storm surges).

Author contributions: Amine Ben Daoued wrote this paper with assistance from Yasser Hamdi, Nassima Mouhous-Voyneau and Philippe Sergent.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements The authors would like to thank François Ropert, a research engineer (CEREMA, centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement) for his thoughtful comments and advices about copula theory application. The authors are grateful to the SHOM (Service Hydrographique et Océanographique de la Marine) for providing data.

References

Antony, C. and Unnikrishnan A.S.: Observed characteristics of tide–surge interaction along the east coast of India and the head of Bay of Bengal. Estuar. Coast. Shelf. Sci. 131, 6–11. doi: 10.1016/j.ecss.2013.08.004, 2013.

Batstone, C., Lawless, M., Tawn, J., et al.: A UK best-practice approach for extreme sea-level analysis along complex topographic coastlines. Ocean Engineering, 71, 28-39, doi:10.1016/j.oceaneng.2013.02.003, 2013.

Beauval, C.: Analyse des incertitudes dans une estimation probabiliste de l'aléa sismique, exemple de la France, Ph.D. thesis, Université Joseph-Fourier, Grenoble, 161 pp., 2003.

Bensi M., and Kanney, J.: Development of a framework for probabilistic storm surge hazard assessment for united states nuclear power plants. SMiRT-23, 2015.

Chebana, F., and Ouarda, T.: Multivariate quantiles in hydrological frequency analysis. Environmetrics, 22: 63–78, doi:10.1002/env.1027, 2011.

Chen, Y., Huang, W., and Xu, S.: Frequency analysis of extreme water levels in east and southeast coasts of china with analysis on effect of sea level rise. Journal of Coastal Research: Special Issue 68 - Climate Change Impacts on Surface Water Systems,105–112, doi:10.2112/SI68-014.1, 2014.

Coles, S.: An Introduction to Statistical Modeling of Extreme Values, Springer, Berlin, 2001.

Coles, S., Tawn, J.: Seasonal effects of extreme surges. Stoch Environ Res Ris Assess, 19, 417–427, doi.org/10.1007/s00477-005-0008-3, 2005.

Dixon, M., and Tawn, J.: Extreme sea-levels at the UK a-class sites: site-by-site analyses. Internal report n°65, Proudman Oceanographic Laboratory - Natural Environment Research Council (UK), 1994.

Dixon, M.J. and Tawn, J.A. Estimates of extreme sea conditions. Extreme sea-levels at the UK A-class sites: site-by-site analyses, Proudman Oceanographic Laboratory report, 65, 228 pages., 1994.

Duluc, C.M., Deville, Y., and Bardet, L.: Extreme sea level assessment: application of the joint probability method with a regional skew surges distribution and uncertainties analysis. Congrès SHF : «Evènements extrêmes fluviaux et maritimes», Paris 1-2 février 2012.

Elineau, S., Duperret, A., and Mallet, P.: Coastal floods along the english channel: the study case of Le Havre town (nw france). Caribbean Waves conference, Guadeloupe. 2013.

Elineau, S., Duperret, A., Mallet, P., and Caspar, R.: Le havre : Une ville cotiere soumise aux submersions marines et aux instabilites de falaises littorales. In: Journées "Impacts du changement climatique sur les risques côtiers", 2010.

Fortunato, A., Li, K., Bertin, K., Rodrigues, M., and Miguez, B.M.: Determination of extreme sea levels along the Iberian Atlantic coast. Ocean Engineering, 111, pp.471- 482. 2016.

~~Salvadori G. and De Michele C.: Frequency analysis via copulas: Theoretical aspects and applications to hydrological events. Water Resour. Res., 40, W12511, doi:10.1029/2004WR003133, 2004.~~

Gouldby, B., Mendez, F., Guanche, Y., Rueda, A. and Mínguez, R.: A methodology for deriving extreme nearshore sea conditions for structural design and flood risk analysis. Coastal Engineering. 88, 15–26. doi: 10.1016/j.coastaleng.2014.01.012, 2014.

Gupta, I.: Probabilistic seismic hazard analysis method for mapping of spectral amplitudes and othe design-specific quantities to estimate the earthquake effects on manmade structures. Journal of Earthquake Technology, 2007.

Haigh, I.D., Nicholls, R., and Wells, N.: A comparison of the main methods for estimating probabilities of extreme still water levels. Coastal Engineering 57(9), 838–849, doi:10.1016/j.coastaleng.2010.04.002, 2010.

Haigh, I.D., Wijeratne, E.M.S., MacPherson, L.R., et al. : Estimating present day extreme water level exceedance probabilities around the coastline of australia: tides, extra-tropical storm surges and mean sea level. Climate Dynamics 42(1-2), 121–138, doi:10.1007/s00382-012-1652-1, 2014.

Haigh, I.D., Wadey, M.P., Ozsoy, O., Wahl, T. et al.: Spatial and temporal analysis of extreme sea level and storm surge events around the coastline of the UK. Sci. Data, 3. 2016.

Hamdi, Y., Bardet, L., Duluc, C.-M., Rebour, V., 2013. Extreme storm surges: a comparative study of frequency analysis approaches, Nat. Hazards Earth Syst. Sci., 14, 2053–2067. doi: 10.5194/nhess-14-2053-2014

Huang, W., Xu, S., and Nnaji, S.: Evaluation of gev model for frequency analysis of annual maximum water levels in the coast of united states. Ocean. Eng. 35(11-12), 1132-1147, doi:10.1016/j.oceaneng.2008.04.010, 2008.

IAEA: Probabilistic safety assessment for seismic events. Tech. rep., IAEA (International Atomic Energy Agency), 1993.

Hussain M.A. and Tajima Y.: Numerical investigation of surge–tide interactions in the Bay of Bengal along the Bangladesh coast. Nat Hazards 86(2):669–694. Doi: 10.1007/s11069-016-2711-4, 2017.

Idier, D., Bertin, X., Thompson, P. and Pickering, M.D.: Interactions Between Mean Sea Level, Tide, Surge, Waves and Flooding: Mechanisms and Contributions to Sea Level Variations at the Coast. Surv Geophys 40, 1603–1630, doi: 10.1007/s10712-019-09549-5, 2019.

Idier, D., Dumas, F., and Muller, H.: Tide-surge interaction in the english channel. Natural Hazards and Earth System Science 12(12), 3709–3718, 2012. doi:10.5194/nhess-12-3709-2012

IRSN: Synthesis of the tsunami generation methods in the numerical tools – probabilistic methods for tsunami hazard assessment. Intern report, 2015.

Kergadallan, X., Bernardara, P., Benoit, M., and Daubord, C.: Improving the estimation of extreme sea levels by a characterization of the dependence of skew surges on high tidal levels. Coastal Engineering Proceedings 1(34), 48, doi:10.9753/icce.v34.management.48, 2014.

Klügel, J.U.: Probabilistic safety analysis of external floods – method and application. Kerntechnik 78(2), 127–136, doi:10.3139/124.110335, 2013.

Krien Y, Testut L, Islam AKMS, Bertin X, Durand F, Mayet C, Tazkia AR, Becker M, Calmant S, Papa F, Ballu V, Shum CK, Khan ZH Towards improved storm surge models in the northern Bay of Bengal. Cont. Shelf Res. 135, 58–73, doi: 10.1016/j.csr.2017.01.014, 2017.

Maspataud, A., Elineau, S., Duperret, A., et al.: Impacts de niveaux d'eau extrêmes sur deux villes portuaires de la manche et mer du nord: Le havre et dunkerque. Journées REFMAR, 2016.

Mattéi, J., Vial, E., Rebour, V., et al.: Generic results and conclusions of re-evaluating the flooding protection in french and german nuclear power plants. eurosafe-forum, 2001.

Nelsen, R.B.: An introduction to copulas, 2nd. New York: SpringerScience Business Media, 2006.

Pirazzoli, P.A. and Tomasin, A.: Estimation of return periods for extreme sea levels: a simplified empirical correction of the joint probabilities method with examples from the French Atlantic coast and three ports in the southwest of the UK. Ocean Dynamics, 57(2), 91-107, 2007.

Pugh, D.T., and Vassie, J.M.: Applications of the joint probability method for extreme sea level computations. Proceedings of the Institution of Civil Engineers 69(4), 959–975, doi:10.1680/iicep.1980.2179, 1980.

Pugh, D.T. and Vassie, J.M.: Applications of the joint probability method for extreme sea level computations. Proceedings of the Institution of Civil Engineers 69(4), 959–975, doi:10.1680/iicep.1980.2179, 1980.

Pugh D.T. and Vassie, J.M.: Extreme sea levels from tide and surge probability. In: Coastal Engineering 1978. American Society of Civil Engineers,. doi:10.1061/9780872621909.054, 1978.

Salvadori G. and De Michele C.: Frequency analysis via copulas: Theoretical aspects and applications to hydrological events. Water Resour. Res., 40, W12511, doi:10.1029/2004WR003133, 2004.

Salvadori, G., De Michele, C., and Durante, F.: On the return period and design in a multivariate framework, Hydrol. Earth Syst. Sci., 15, 3293–3305, https://doi.org/10.5194/hess-15-3293-2011, 2011.

Sklar, M.: Fonctions de répartition à n dimensions et leurs marges. Université Paris 8. 1959.

TAWN, J., and VASSIE, J.M.: Extreme sea levels: the joint probabilities method revisited and revised. Proceedings of the Institution of Civil Engineers 87(3), 429–442, doi:10.1680/iicep.1989.2975,1989.

~~F.~~F.E.M.A.: Final draft guidelines for coastal flood hazard analysis and mapping for the pacific coast of the united states. Tech. Report. FEMA, 2004. URL http://www.fema.gov/library/viewRecord.do?id=2188S

US-NRC: Reactor safety study. an assessment of accident risks in u.s. commercial nuclear power plants. executive summary: main report. Tech. rep., US-NRC, 1975.

US-NRC: Tornado climatology of the contiguous united states. Tech. rep., Office of Nuclear Regulatory Research, 2007.

USACE: Coastal storm hazards from virginia to maine. Tech. rep., USACE (2015)

Ver Hoef, J.M. (2012). Who invented the delta method?. *The American Statistician*. 66 (2): 124–127. *doi:10.1080/00031305.2012.687494*

Walden, A., Prescott, P., Webber, N.: An alternative approach to the joint probability method for extreme high sea level computations. Coastal Engineering 6(1), 71–82, doi:10.1016/0378-3839(82)90016-3, 1982.

Williams, J., Horsburgh, K.J., Williams, J.A., and Robert. N.F.P : Tide and skew surge independence: New insights for flood risk, Geophys. Res. Lett., 43, 6410–6417, doi:10.1002/2016GL069522, 2016.

Table 1: Sea level and rainfall data sets

Type	Station	Period	Time step
Sea level	Harbour	1971~~38~~-2015~~7~~	1h
Rainfall~~Rainfall~~	Cap-de-la-Heve~~Harbour/Perret/Cap-de-la-Heve~~	2005-2018 ~~1997-2005~~	6'~~1h~~
~~Rainfall~~	~~Cap-de-la-Heve~~	~~2005-2018~~	~~6'~~

Table 3~~2~~: Sea RLs and 95% confidence intervals for the three fitting procedures (in meters)

Method	T=10	T=50	T=100	T=1000
JPM-SSS	8.31 (8.27-8.35)	8.77 (8.72-8.82)	8.89 (8.84-8.95)	9.20 (9.07-9.32)
JPM-MSS	8.84 (8.79-8.89)	9.29 (9.22-9.36)	9.42 (9.33-9.51)	9.79 (9.58-10.01)
Frequency Analysis - ESL	8.82 (8.74-8.91)	8.99 (8.80-9.18)	9.05 (8.79-9.31)	9.22 (8.67-9.77)

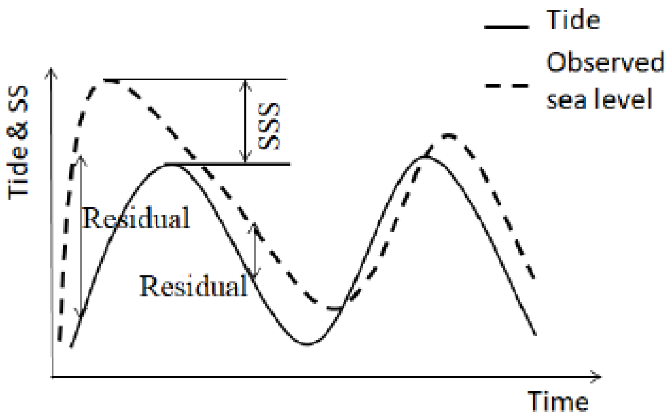


Figure 1: Definition and schematic representation of a skew storm surge

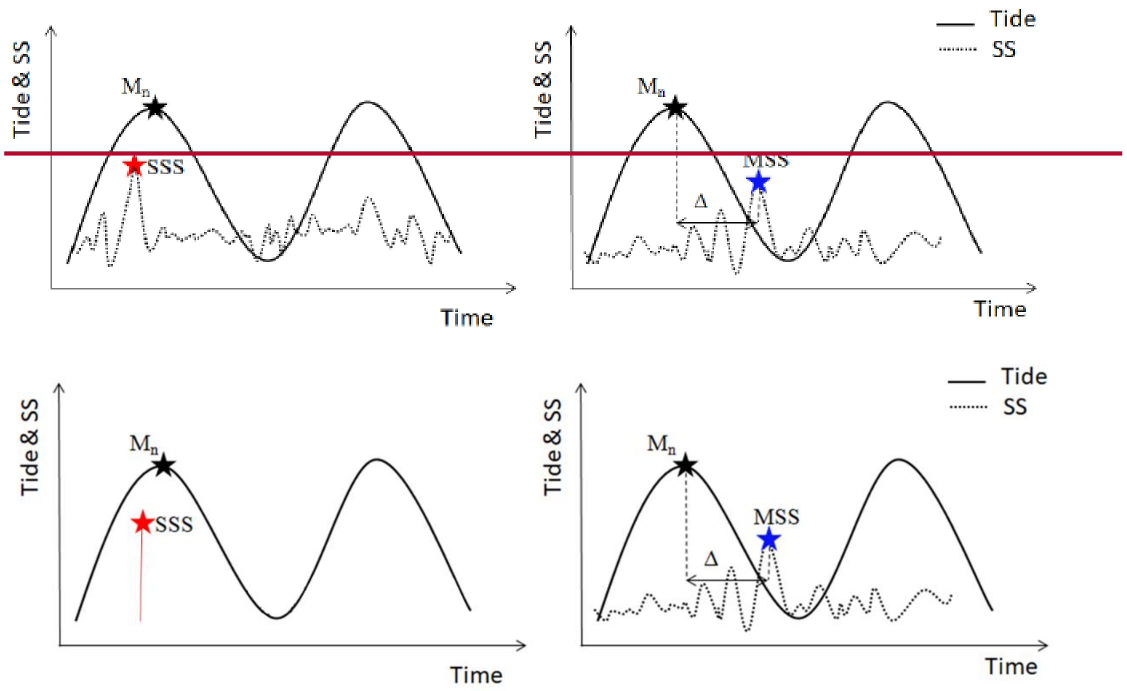
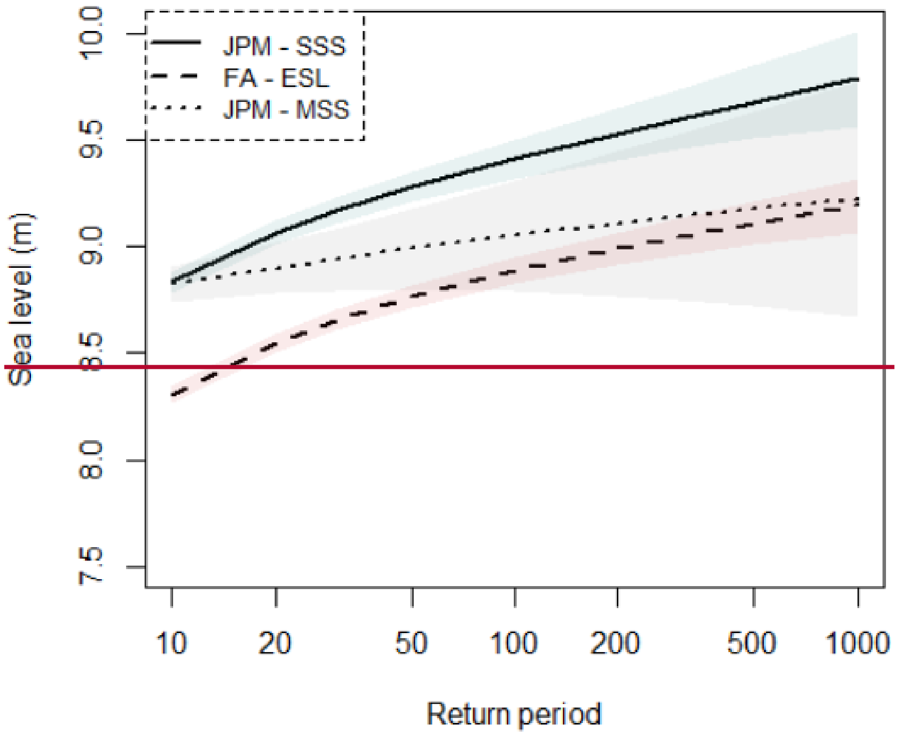


Figure 2: Illustration of tide and storm surge signals for the of joint surge-tide probability procedures: (left) skew surge-tide combination; (right) maximum surge - tide combination

Figure 3: Case study (Le Havre): location map



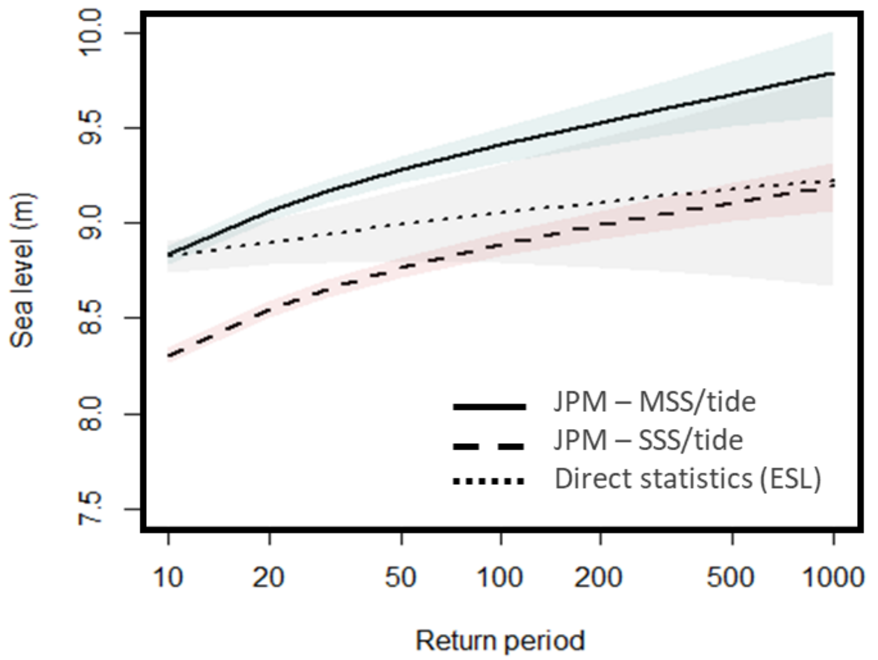


Figure 64: Sea level quantiles and confidence intervals

figure 4 shows that extreme sea level events tend to occur at the time of the high tide