Reviewer 1 :

General Suggestions

Review on the paper "A nonstationary analysis for investigating the multiscale variability of extreme surges: case of the English Channel coasts"
General comments
In the research manuscript, the authors present an analysis of time series of storm surges in five stations along the coast of the English Channel.
The study is two-fold: a first part is related to the analysis of the monthly extreme storm-surges signals, by using a multi-scale wavelet analysis in order to describe the

Answer to Reviewer 1 :

Thank you for the different suggestions and comments useful for the improvement of the manuscript.

The text of **the manuscript has been checked by the authors and has been simplified to make easier the writing and the understanding of the different sections, in particular the** discussion and the methodology.

Also, some information has been moved from the methodological part to the results. Two illustrations related to the original hydrodynamic data (Figure 4 in the new version) and the morphological defects (Figure 2 in the new version).

The answers will be addressed for each specific comment.

2. Data

It no very clear in the paper if storm surge or the sea level height data is used. Only the later is measured by the tide gauge, and thus a pre-processing step is required to filter out the tides and the sea-level rise. The description of this pre-processing seems to be missing in the paper. Another question is about the availability of the large-scale atmospheric circulations indices (NAO, AMO...) during the whole period covered by the tide gauges. In particular, the Brest station has measurements from 1850, so one could wonder if the indices are available from the date, and what could be the quality of such values. I think that the paper could benefit from some discussion on this point.

Answer

Thank you for this suggestion.

According to the determination of surges, a new part explaining this extraction has been added in the new version: part 3.1;

According to the availability of the large-scale atmospheric circulations indices (NAO, AMO…), they have been extracted from the NCEP-NCAR Reanalysis fields with the same period of the surges.

Timeseries of surges

Weymouth: 1991-2018

Brest: 1846-2018

Dunkirk:1964-2018

Dover: 1958-2018

Cherbourg: 1964-2018

Timeseries of the correlations Climate index - maximum surges

The correlation has been carried depending on the length of the

AMO/BREST: 1880 – 2017

NAO /Brest : 1865-2017

SLP /Brest : 1948-2017

ZW /Brest : 1865-2017

AMO – NAO – SLP - ZW/ Cherbourg - Dunkirk : 1964-2017

AMO – NAO – SLP - ZW/Douvres : 1958-2017

AMO – NAO – SLP- ZW/Weymouth : 1991-2017

The methodological approach has benefit from this information.

3. Extreme value models

The authors use the classical extreme value distribution (GEV) to model the monthly maxima of storm surges, making the distribution non-stationary by incorporating climate indices as covariates.

Although the presentation of the model is rather clear, the data on with the model is applied is not as clear to me: is it on the initial time series of storm surges or on the spectral components? On L200, it seems that the model is applied to each spectral component, but the justification of using a GEV distribution is then questionable since the component by itself is not extreme nor a maxima, and thus an extreme value distribution is not justified. Marginal distributions of the variable on which the GEV is fitted could give some insight on the adequacy of a GEV, in addition to the QQ plots of Figure 10.

I have another remark about model selection: the authors do not show the fitted parameters values nor the associated confidence intervals, but only the AIC values in Table 3. Such values would be necessary to address the fit and to discuss whether or not the influences of the indices are significant. The authors are only selecting the parameter that cannot be considered are stationary, but not the index that is relevant to explain the non-stationary.

Answer

The authors try to add more clarifications related to the application of the GEV model.

Indeed, the maxima of surges has been decomposed to different frequencies to which the model has been applied. This approach has been applied by Turki et al., 2019 ; 2020. The low and the high frequencies of the maxima highlight the different fluctuations of the signal and their multiscale variability. The prediction of each fluctuation has been investigated by the use of nonstationary GEV model with the incorporation of climate indices.

4. Multi-timescale variability of extreme surges

The authors describe the results of the continuous wavelet transform (CWT) on the monthly maxima of storm surges to assess the non-stationary behavior;

Answer

The authors have used the CWT to identify the spectrum of the extreme signal and its distribution in space (between station) and time (during the period of study); (Figure 2).

The authors have shown also (Fig 3) that the low frequencies (lower than 10 year) are clearly observed from the CWT of the extreme surges, and less identified from the mean surges.

In this part, a quantification of the spectral components has been presented (Figure 4).

5. Large-scale climate North-Atlantic oscillations and their link to extreme surges in the English Channel

This section is two-fold : first, exhibit the link between the indices and the monthly maxima of storm surges and fit the GEV distribution to the components of the storm surge.
The authors look at the wavelet coherence to address this question and conclude that:
Each timescale exhibits mainly strong links with its associated climate index (L313)
Such a conclusion seems rather obvious to me because the indices are constructed that way and is not sufficient to my point of view to do variable selection in the GEV model of the following section before fitting the model.

Although the lengthy discussion about the visual inspection is interesting and may worth it, a proper statistical method to select the variable should be preferred.
Once the model is fitted, the paper falls short : since there is no variable selection and no use of the fitted model, what is the fit used for? We only can see with some difficulties the return levels of each component for the Brest station, but with little extrapolation.
As is, the relevance of using a GEV model is questionable.

Answer

Thank you for these suggestions.

Indeed, according to the previous works, the effects of the climate patterns is important and should be considered for predicting the variability of extreme surges.

In the present research, the novel approach that an excellent prediction of the total signal requires a good multi-timescale prediction, i.e a prediction of each spectral component (provided by the MODWT analysis) which is described by an appropriate climate index (the most appropriate one has been selected basing on the wavelet coherence and the monte carlo iterations for each component).

Indeed, the non-linear interaction between the physical mechanisms of climate patterns is very complex and could not considered at the same time to predict the extreme surges. To investigate this interaction our hypothesis consists on developing a statistical model able to predict the spectral component with the incorporation of the most adequate climate information.

The development of a full model useful for estimating the extreme surges needs the integration of the GEV models associated to the different timescales (~ 2-4 years; ~ 5-8 years; ~ 12-16 years) by the means of mathematical methods; which is the objective of the further works. The present work bring a novel hypothesis to resolve the complex effects of climate patterns on the local variability of surges. This step is very important to introduce a new model considering the different timescales of extreme surges.

Answer

All figures have been improved in terms of quality.

Technical remarks

- Spacing is not uniform in the text, please consider proof-reading;
- Parameters values are missing in Table 3;
- a Â˝u on L805; - Brest is missing in Figure 1; On L150:
*The observations which correspond to the hydrographic zero level are referenced to zero tide gauge (Figure 1)
* but seems missing;
- Figures 2-3-5-6-7-8 : the time-scales can hardly be seen, please choose another color or another representation or another colormap.
- Figure 2 color bar is not coherent with the other Figures;
- Figures 4 and 9: the x-axis is not clear, at least 4-digit years should be provided.
- Figure 10 a : The y-axis should be "Modeled values";
- Figure 10 b: the figure can hardly be read, please provide a larger version or a better quality (e.g. SVG)

Reviewer 2 :

General Suggestions

The manuscript by Turki and co-authors addresses an important issue for the modeling of exceedance probability of extreme surges namely accounting for the dependence with climate patterns. The authors present an approach relying on wavelet analysis to investigate the correlation between the extreme surges and four climate oscillations (North Atlantic Oscillation, and Atlantic Multidecadal Oscillation, and the ones related to Sea-Level Pressure and Zonal Wind) at multiple time scales, _1.5-years, _2-4-years, and _5-8-years and 12-16-years. On this basis, they perform nonstationary extreme value analysis using the English Channel coasts as application cases and show the added-value for accounting for these multiscale processes when deriving the return periods.

Main comment

The manuscript is well organized and the presentation is clear. Yet, several aspects should be clarified and further elaborated before publication (state of the art, details of the implementation, discussion regarding the assumptions). Therefore, I recommend additional corrections by incorporating, if possible, the following recommendations.

Answer to Reviewer 2 :

Specific comments

1. State of the art.

Some key references about the link between extreme surges and climate variables should be added to the bibliography, namely:

** Marcos, M., Calafat, F.M., Berihuete, Á., Dangendorf, S., 2015. Long term variations in global sea level extremes. J. Geophys. Res. 120(12), 8115-8134.

** Marcos, M.; Woodworth, P.L., 2017. Spatiotemporal changes in extreme sea levels along the coasts of the North Atlantic and the Gulf of Mexico. J. Geophys. Res., 122(9), 7031-7048.

** Méndez, F. J., Menéndez,M., Luceño, A., Losada, I. J., 2007. Analyzing monthly extreme sea levels with a time-dependent GEV model. Journal of Atmospheric and Oceanic Technology 24(5), 894-911.

** Wahl, T., Chambers, D.P., 2015. Evidence for multidecadal variability in US extreme sea level records. J. Geophys. Res. 120, 1527–1544.

** Wahl, T.; Chambers,D.P., 2016. Climate controls multidecadal variability in US extreme sea level records. J. Geophys. Res. 121(2), 1274-1290.

My second concern relates to the differences of the present work with the recently published one, namely Turki et al. (2020). As far as I understood, the time scale 12- 16-years and the British part of the Channel coasts were not tackled in this published work, but it would be useful to situate in more details the present study with respect to Turki et al. (2020), for instance in the introduction.

Thank you for the comments.

The proposed references have been revised and added to the state of the art.

The new funding proposed in this research, compared to the last work of Turki et al., 2020, has been better explained in the state of the art as suggested in line …….

2. Details on the implementation.

The authors focus on extreme surges. To do so, the raw data of tide gauges should be pre-processed by accounting for the tide. Could the authors provide more details on how they proceeded? What type of tide data did they used?

Similarly, the authors used climate indices provided by the NCEP-NCAR Reanalysis.
Could the authors provide the web link where they downloaded the data for the climate indices? Besides, the authors mentioned climate oscillations using SLP and Zonal Wind. Are they directly available from NCEP-NCAR Reanalysis or are they derived from a pre-processing using EOF analysis for instance?
3. Model selection in the non-stationnary Extreme Value Analysis (EVA). Integrating the climate drivers as covariates in EVA is a good idea, but the selection of the 'most appropriate' model deserves more discussion.

Regarding the extraction of extreme surges, more details related to the classical model used for calculating tides are provided in the new version.

Also, the different climate indices have been better explained.

The selection of the most appropriate GEV model has been achieved for each frequency component. The use of the climate information has been differently explained for the different spectral component. For each frequency, the different climate indices have been tested to analyze the nonstationary behavior of the component. Then, the climate index associated with the best model fitting data (i.e. showing the lowest AIC) has been selected and presented in this research. Similar approach has been used in Turki et al., 2020.

More explanations related to this part has been added in the new version.

3.1. Adequacy of GEV.

It is not clear to me whether extreme value distributions are applied to each spectral component. If so, I wonder whether these variables are 'extreme', and whether GEV distribution is appropriate. Could the authors comment on that?

The monthly extreme surges have been calculated from hourly residual sea level. This signal has been decomposed by the MODWT to study separately the different components. Our hypothesis in the present research is the following:

The variability of the local extreme surges should be explained by the global climate patterns described by a series of physical mechanisms associated to the climate indices.

We have used the hypothesis that each spectral should be explained by a climate mechanism. Such hypothesis has been justified and validated by (1) the coherence diagrams (see also Table 2) where we have demonstrated that the effect of each climate index on the variability of extreme surges varies as a function of the spectral component and (2) the monte carlo analysis applied to each spectral component to select the most appropriate climate index. This analysis has shown a strong coherence with the first validation (1).

3.2. Variable selection.

Table 2 is used to select the most appropriate climate variables to be integrated in the EVA. Though informative and useful to support discussion, my concern is that this selection is mainly based on a correlation analysis (Figure 7 and following ones), and I wonder why the authors did not perform a variable selection for the GEV model directly; for instance using AIC or selection criteria. See a discussion by Wong (2018).

Answer

Thank you for this comment.

Here, a Bayesian estimation has been used to make inferences from the Likelihood function. The reason behind the choice of this approach is overcoming the limitation of short time-series with small size, the case of Weymouth station where date cover the period from 1991 and 2018.

For each spectral component, a sample of 100.000 length has been modelled by GEV using a selected climate index. The upper and lower quantiles of the posterior probability distribution for the parameters of the MCMC sample are taken. The goodness of fit has been taken as a function of the values of the upper and the lower quantiles; best results have been considered when these values are higher than 92.5% and lower than 5.2%, respectively.

A new section has been added in the methodological Approach

4 Determination of the most appropriate climate oscillation 271 *connected to each timescale extreme surges for GEV models*

Then and once selected, the most appropriate climate index has been incorporated into the GEV covariates (into the different parameters). By the use of AIC criteria, we have the best

results of fitting for the incorporation of this index into one (location only), two (location and scale) or three (location, scale or shape) parameters of GEV.

Also, More clarifications related to this point have been added in the results (lines 573-581 of the new version pfd)

3.3 Model selection.

Furthermore, the results for Brest in Table 3 may raise some questions:

- For scale_12-16 years, GEV0 does not seem to be the model that leads to the minimum AIC value (-1258 to be compared to -1980 for GEV1);

- For scale _ 2-4-yr, the AIC values

fro GEV1-3 are very close, which make very hard to identify with high confidence the most appropriate model. The authors should comment on that.
See also Burnham and Anderson (2004) for further details.
Reference:
Wong, T. E. (2018). An integration and assessment of multiple covariates of nonstationary storm surge statistical behavior by Bayesian model averaging. Advances in Statistical Climatology, Meteorology and Oceanography, 4(1/2), 53-63.

Burnham, K. P. and Anderson, D. R.: Multimodel inference: understanding AIC and BIC in model selection, Sociolog. Meth. Res., 60, 261–304, 2004.

It's a very interesting comment which needs more clarifications from the authors.
More discussion related to this part has been added basing on the references provided.
Also, the different results presented here still preliminary and represent a first step for investigating the nonstationary behavior of the different frequencies. Preliminary results have shown that the nonstationary behavior is mainly controlled by the high frequencies.

4. Correlation.

The authors analyze the significance of the correlation through a visual inspection of the results provided by wavelet spectral analysis. In lines 339-341, the authors mentioned that they are using a Monte-Carlo-based approach to identify the most statistically significant correlation: could the authors provide more details on the implementation.
Is it a bootstrap-based approach? How do they analyse the changes of the

correlation at the Monte-Carlo iterations? Could the authors provide additional results about this significance assessment?

Answer

As suggested in the previous document, a bootstrap approach has been applied to assess the statistical significance of the correlation between the spectral component of the extreme surges and the climate oscillation at each timescale. By resampling the timeseries 10.000 times, 95% confidence intervals have been considered to extract the best climate information fitting the extreme surges (Villarini et al., 2009).

Here, the confidence intervals (CI) have been calculated by the bootstrap technique by simulating the monthly maxima of surges (spectral component) from the climate index (spectral component) at each timescale (new samples with a size of 1000).

When the original surges have been fitted to the simulated ones, 95% confidence intervals for the maximum likelihood estimates have been calculated.

A table providing the 95% CI for each spectral component and each station is added (Table 3).

Table 3 Analysis of the statistical significance of the correlation between the spectral component of the extreme surges and the climate oscillation at each timescale for the different stations. The 95% Confidence Intervals from Bootstrap technique in Square Brackets. The most significant correlations are illustrated by the grey columns.

~ 1.5-yr	SLP	ZW	NAO	AMO
Brest	[0.152, 0.174]	[0.145, 0.182]	[0.141, 0.178]	[0.138, 0.189]
Cherbourg	[0.161, 0.170]	[0.142, 0.179]	[0.142, 0.179]	[0.135, 0.180]
Dunkirk	[0.160, 0.168]	[0.150, 0.185]	[0.150, 0.185]	[0.135, 0.183]
Dover	[0.158, 0.165]	[0.161, 0.180]	[0.161, 0.180]	[0.133, 0.180]
Weymouth	[0.421, 0.429]	[0.411, 0.450]	[0.381, 0.299]	[0.375, 0.281]
~ 2-4-yr				
Brest	[0.145, 0.164]	[0.149, 0.158]	[0.141, 0.179]	[0.138, 0.183]
Cherbourg	[0.160, 0.175]	[0.188, 0.196]	[0.161, 0.179]	[0.158, 0.182]
Dunkirk	[0.145, 0.158]	[0.180, 0.185]	[0.145, 0.164]	[0.140, 0.169]
Dover	[0.148, 0.163]	[0.192, 0.198]	[0.145, 0.168]	[0.143, 0.175]
Weymouth	[0.412, 0.420]	[0.420, 0.430]	[0.410, 0.425]	[0.410, 0.428]
~ 5-8-yr				
Brest	[0.075, 0.090]	[0.073, 0.092]	[0.085, 0.089]	[0.070, 0.096]
Cherbourg	[0.190, 0.198]	[0.185, 0.198]	[0.191, 0.196]	[0.181, 0.198]
Dunkirk	[0.180, 0.188]	[0.177, 0.185]	[0.183, 0.187]	[0.175, 0.187]
Dover	[0.180, 0.195]	[0.180, 0.198]	[0.180, 0.184]	[0.176, 0.199]
Weymouth	[0.219, 0.222]	[0.218, 0.225]	[0.221, 0.226]	[0.216, 0.226]
~ 12-16-yr				
Brest	[0.033, 0.046]	[0.034, 0.045]	[0.035, 0.045]	[0.038, 0.041]
Cherbourg	[0.089, 0,099]	[0.090, 0,099]	[0.090, 0,097]	[0.091, 0,095]
Dunkirk	[0.087, 0.099]	[0.089, 0.098]	[0.090, 0.097]	[0.093, 0.096]
Dover	[0.078, 0.089]	[0.080, 0.088]	[0.080, 0.086]	[0.082, 0.085]
Weymouth	[0.250, 0.260]	[0.250, 0.259]	[0.250, 0.257]	

Model for each Spectral component?

The objective of this decomposition and the use of GEV par component. The full model for estimating the extreme surges can be the sum of the different components?

Answer

In any part of the manuscript, the authors have proposed the sum of the different GEV models to obtain the full model able to estimate the total signal of monthly extreme surges.

Indeed, this question remains unresolved until now. Once the model identified, how can we use them to define a stochastic tool for estimating the extreme surges?

However, this finding confirms our first hypotheses related to the connection between the most appropriate climate index and the extreme surges at each time scale. It provides also a guidance on incorporating nonstationary processes of large-scale oscillations to different spectral components informed by the wavelet techniques, the Bayesian approaches and the GEV model probabilities.

A new paragraph explaining this point has been added as a discussion part.

This study has expanded the previous works of Turki et al. (2019; 2020) upon a new approach combining spectral and probabilistic methods to integrate multiple streams of information related to climate teleconnections. Indeed, each timescale has been simulated separately with the nonstationary GEV models and expressed as a function of the most suitable climate index improving its fitting. The estimation of the total signal of surges should be determined by combining the developed nonstationary GEV models used for the different timescales. These results should support the hypothesis introduced at the beginning of the present work suggesting that: (i) the extreme surges should depend on different timescales; (ii) each timescale should be related to a specific large-scale oscillation. The finding is in agreement with the previous works of Lee et al. (2017) and Wang et al. (2018) highlighting the importance of a careful consideration when complex physical mechanisms of different climate indices are included into model structures for estimating extreme surges.

Indeed, this work provides a guidance on incorporating nonstationary processes of large-scale oscillations to different spectral components informed by the wavelet techniques, the Bayesian approaches and the GEV model probabilities.

The primary contribution of the present research is to present a new approach for: (1) investigating the multi-timescale variability of the nonstationary extreme surges; (2) identifying their multi-connection with climate oscillations according to the timescale and (3) resolve in part the problems of uncertainty of most appropriate climate to use as covariate for GEV models at each timescale. However, additional models (e.g. significance tests and sensitivity analyses and modelling uncertainties) and application sites (e.g. Mediterranean and pacific ones controlled by other climate oscillations) are required to expand the developed approach.

Also, generating a final robust stochastic model useful for projecting storm surge return levels and assessing the flood risk management requires further efforts to build on the potentially advantageous approach presented here by integrating the GEV models associated with the different timescales through the use of mathematical methods.

Figures for comparing the return levels.

Answer

Here, the stochastic modelling provides us some insights into the nonstationary behavior of extremes in relation with the climate oscillations.

The comparison between the simulated surges, using the nonstationary GEV models, and the original data has been illustrated in Fig.10 for Brest.

The fifty-year return level plot for the different spectral components is presented in Fig.10 c.

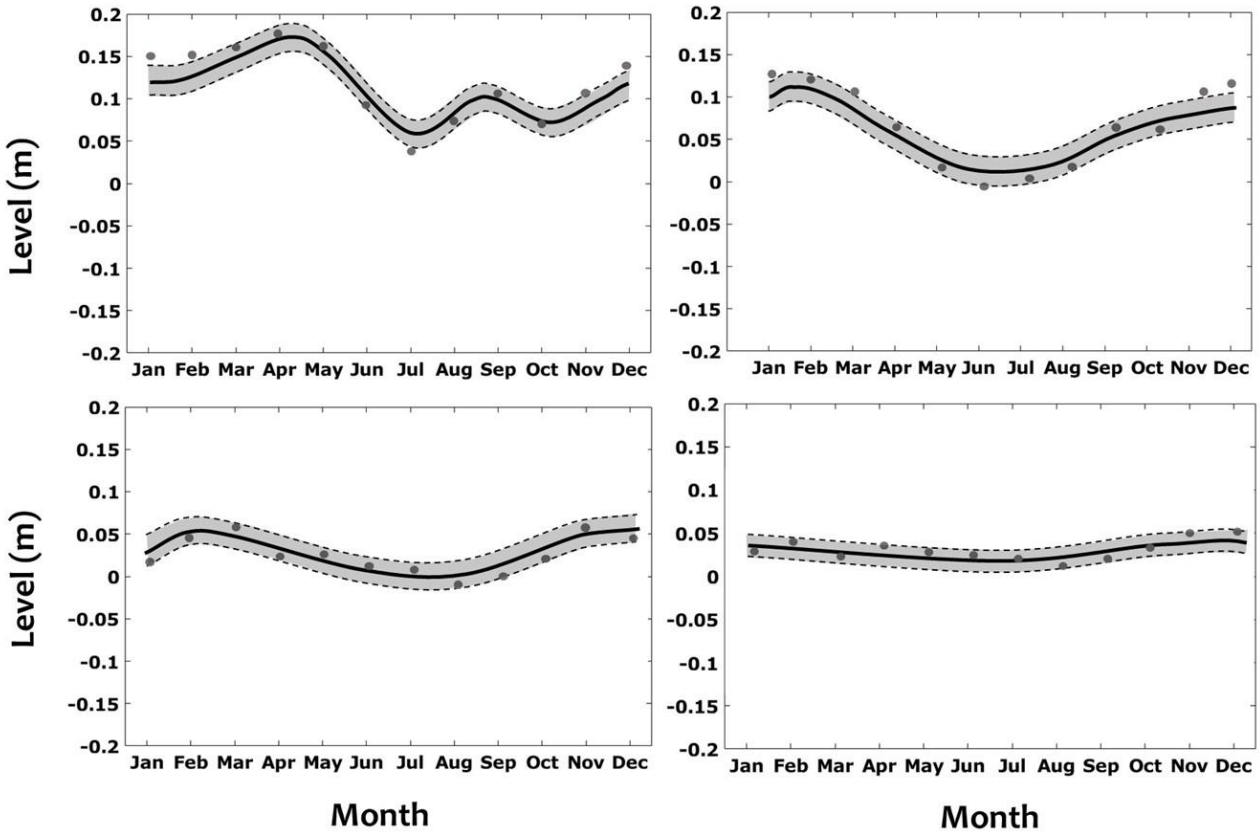

Figure 10.c Fifty-year return level of monthly values using the original data (grey circles) and the best nonstationary GEV model for Brest (solid black line) at each timescale (spectral component). The lower and the upper limits of the 95% confidence interval calculated using the delta method (dashed black line). The associated confidence area is plotted with grey shaded area.

5. Typo.

Line 70: "investigates" should be "investigate" Line 467: "covariable" should be covariate

All typos have been checked and corrected.

A nonstationary analysis for investigating the multiscale variability of extreme surges: case of the English Channel coasts

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Abstract

This research examines the nonstationary dynamics of extreme surges along the English Channel coasts and seeks to make their connection to the climate patterns at different time-scales by the use of a detailed spectral analysis in order to gain insights on the physical mechanisms relating the global atmospheric circulation to the local-scale variability of the monthly extreme surges. This variability highlights different oscillatory components from the interannual (~1.5-years, ~2-4-years, ~5-8-years) to the interdecadal (~12-16-years) scales with mean explained variances of ~ 25 - 32 % and ~ 2 - 4 % of the total variability, respectively. Using the two hypotheses that the physical mechanisms of the atmospheric circulation change according to the timescales and their connection with the local variability improves the prediction of the extremes, we have demonstrated statistically significant relationships of ~1.5-years, ~2-4-years, and ~5-8-years and 12-16-years with the different climate oscillations of Sea-Level Pressure, Zonal Wind, North Atlantic Oscillation and Atlantic Multidecadal Oscillation, respectively.

Such physical links have been used to implement the parameters of the time-dependent GEV distribution models. The introduced climate information in the GEV parameters has considerably improved the prediction of the different time-scales of surges with an explained variance higher than 60%. This improvement exhibits their nonlinear relationship with the large-scale atmospheric circulation.

Key-Words*:* Coastal extreme surges, multi-timescale variability, climate oscillations, nonstationary GEV models

1. Introduction

Risks assessments has been recognized as an urgent task essential to take effective reduction of disasters and adaptation actions of climate change. The increase in coastal flood risk is generally driven by the extreme surges being the result of episodic water fluctuations due to waves and storm surges. High surges are considered as significant hazards for many low-lying coastal communities (e.g. Hanson et al., 2011; Nicholls et al., 2011) and are expected to be intensified with rising global mean sea level (Menendez and Woodworth, 2010).

Being an alarming problem for the coastal vulnerability, extreme events have gained the attention of the scientists who have reported the dynamics (e.g. Haigh et al., 2010; Idier et al., 2012; Masina and Lamberti, 2013; Tomasin and Pirazzoli, 2008; Turki et al., 2020) and the projections (e.g. vousdoukas et al., 2017) of extreme surges considering the stationary and the nonstationary contributions from tides, waves, sea-level-rise components (e.g. Brown et al.,

491 2010; Idier et al., 2017), and large-scale climate oscillations (e.g. Colberg et al., 2019; Turki et
492 al., 2019; 2020).
493 Under the assumption of a stationary surges, the concepts of return level and return period
494 provide critical information for infrastructure design, decision-making, and assessing the
495 impacts of rare weather and climatic events (Rosbjerg and Madsen, 1998). However, the
496 frequency of extremes has been changing and is likely to continue changing in the future (e.g.
497 Milly et al., 2008). Therefore, concepts and models that can account for nonstationary analysis
498 of climatic and hydrologic extremes are needed (e.g. Cooley, 2013; Salas and Obeysekera,
499 2013; Parey et al., 2010).
500 Over the last decade, several studies adopted the nonstationary behaviour of extremes to
501 estimate their evolution and their return-periods from rigorous models of Extreme Value
502 Theory (EVT) by incorporating an information related to climate oscillations.
503 In this way, the recurrence of coastal extreme events over the Northern European continent and
504 the persistence of high energetic conditions around the Atlantic have been associated with the
505 deepening of Icelandic Low and the extension/reinforcement of the Azores High. Those facts
506 can be interpreted, at quasi daily timescale, as the preferred excitation of a given atmospheric
507 regime close to the positive phase of the North Atlantic Oscillation. The recent predominance

508 of this regime can be explained partly by the impact of the North Tropical Atlantic Ocean upon
509 the midlatitude atmosphere and by the increase of greenhouse gas concentration induced by
510 human activities.
511 Menendez and Woodworth (2010) have used a nonstationary extreme values analysis together
512 with the NAO (North Atlantic Oscillation) and Arctic Oscillation (AO) indices for improving
513 the estimation of monthly extreme sea-levels along the European coasts.
514 In the Northern Adriatic region, Masina et al. (2013) investigate changes in extreme sea levels
515 applying a nonstationary approach to the monthly maxima and the climate oscillations of NAO
516 and AO (Arctic Oscillation) indices. They have suggested that the increase in the extreme water
517 levels since the 1990s is related to the changes in the wind regime and the intensification of
518 Bora and Sirocco winds after the second half of the 20th century.
519 Then, Marcos et al. (2015) have investigated the decadal and multidecadal changes in sea level
520 extremes using long tide gauge records distributed worldwide. They have demonstrated that
521 the intensity and the occurrence of the extreme sea levels vary on decadal scales in the most of
522 the sites in relation with a common large-scale forcing. In the same way, the study of extreme
523 sea levels along the coastal zones of the North Atlantic Ocean and the Gulf of Mexico has
524 shown that the mean sea level should be considered as the major driver of extremes (Marcos

525 and Woodworth 2017) since the intensity of extreme episodes increases at centennial time
526 scales, together with multidecadal variability. The extreme sea levels along the United States
527 coastline between 1929 and 2013 have been investigated by Wahls and Chambers (2015;
528 2016). Wahls and Chambers (2015) have identified the relation between the multidecadal
529 variations in extreme sea and the changes in mean sea level. Such relation has been mainly
530 pointed toward some regions where storm surges are primarily driven by extratropical cyclones
531 and should contribute in the variation of relevant return water levels required for coastal design.
532 Such extremes have been then investigated in Wahls and Chambers (2016) works aiming to
533 define their relationship with the large-scale climate variability by the use of simple and
534 multiple linear regression models.
535
536 In the English Channel, the extreme sea levels have been addressed by several works (e.g.
537 Haigh et al., 2010; Idier et al., 2012; Tomasin and Pirazzoli, 2008; Turki et al., 2015a; Turki et
538 al., 2019) with the aim of investigating their dynamics at different timescales and their
539 connections to the atmospheric circulation patterns.
540 Haigh et al. (2010) investigated the interannual and the interdecadal extreme surges in the
541 English Channel and their strong relationship with the NAO index. Their results showed weak

542 negative correlations throughout the Channel and strong positive correlations at the boundary
543 along the Southern North Sea. Using a numerical approach, Idier et al. (2012) studied the spatial
544 evolution of some historical storms in the Atlantic Sea and their dependence on tides.
545 Recently, Turki et al. (2019) have examined the multiscale variability of the sea-level changes
546 in the Seine bay (NW France) in relation with the global climate oscillations from the SLP
547 composites; they have demonstrated dipolar patterns of high-low pressures suggesting positive
548 and negative anomalies at the interdecadal and the interannual scales respectively.
549 Despite these important advances, no particular studies exist on sea-level dynamics and
550 extreme events linked to the large-scale climate oscillations along the English Channel
551 coastlines. The aforementioned works of Turki et al. (2015a, 2019) have focused on the
552 multiscale sea-level variability along the French coasts related to the NAO and the Sea-Level
553 Pressure (SLP) patterns; however, they have not addressed the regional behaviour of the
554 extreme sea levels in relation with the global climate oscillations.
555 Then, similar approaches have been used by Turki et al. (2020) to quantify the nonstationary
556 behaviour of extreme surges and their relationship with the global atmospheric circulation at
557 different timescales along the English Channel coasts (NW France) between 1964 and 2012.
558 They have reported that the intermonthly and the interannual variability of monthly extrema

559 are statistically modelled by nonstationary GEV distribution using the full information related
560 to the climate teleconnections.
561 In the same context, the present contribution aims to investigate the interannual and the
562 interdecadal dynamics of extreme surges along the English Channel coasts (NW France and
563 SW England) by the use of combining techniques of spectral analyses and probabilistic models.
564 We hypothesize that different large-scale climate variables may be involved in explaining the
565 occurrence of extreme surges, and that this dependence can be a function of each timescale.
566 The rationale behind this hypothesis is based on the following: (1) each timeseries of extreme
567 surges should depend on different timescales; (2) each timescale should be related to a specific
568 large-scale oscillation. Using this hypothesis, the linkages between the local extreme surges
569 and the large-scale climate oscillations are deciphered with the aim to improve the extreme
570 models using the most consistent large-scale oscillations as covariates.
571
572 The overall approach for testing our hypotheses can be described as follows, for a given
573 extreme surge timeseries: i) identify the short to long timescale oscillations characterizing the
574 local variability of the extreme surges; ii) explore the correlation between the local extreme
575 surges and the selected large-scale variable from short to long timescales; iii) select the most

appropriate large-scale variable as an explanatory parameter to be used as a covariate in nonstationary GEV models and estimate the extreme surges.

The paper is structured as follows. The used hydro-climatic data are presented in section 2, including local extreme surges and large-scale variables. Section 3 explains the methodological approach used. Finally, the sections 4 and 5 report the results related to the multiscale variability of extreme surges along the English Channel and their teleconnections with the large-scale climate oscillations required for their estimation by the use of GEV extreme models. The concluding remarks of these findings are addressed in section 6.

2. Database description

The present research focuses on the dynamics of extreme surges along the English Channel coasts (French and the Britannic coasts); It has been conducted in the framework of some French research programs: RICOCHET (ANR program), RAIV COT (Normandy Region program) and the international project COTEST (CNES-TOSA program) related to the future mission Surface Water and Ocean Topography (SWOT).

The English Channel (Figure 1) is a shallow sea between Northern France and South England, connecting Atlantic Ocean to North Sea. Melting of retreating glaciers formed a megaflood in the southern North Sea and it geographically separated Britain from Europe and formed English

Channel at the last Quaternary Period (Collier et al. 2015). English Channel has a complex sea floor due to its characteristics of formation. It is deep and wide on the western side, narrower and shallower towards Strait of Dover. Largest width of the Channel is around 160 km (Figure 1). The average depth of the channel is about 120 m. It gradually narrows eastward to a width of 35 km and depth of around 45 m in the Dover Strait. The east to west extent of the Channel is about 500 km. The overall width of shallow depths is wider in the French side of the channel. The extreme storm surges of this area are mostly occurred by low pressure systems from the Atlantic Ocean, propagating eastwards or storm surges propagating south from the North Sea (Law, 1975). The area is exposed to major storms from Atlantic side of the channel, having a maximum fetch of winds, from west to southeast then to northwest.

Three tide gauge sites along the French coasts have been used in the present study: (1) Dunkirk station which is a few kilometres away from Belgian borders, (2) Cherbourg station located on the Cotentin Peninsula and at the opening of the Atlantic Sea, (3) Brest station which is a sheltered bay located at the western extremity of metropolitan France and connected to the Atlantic Ocean.

609 Two tide gauge sites along the Britannic coats have been used: (1) Dover station which is
610 separated from Dunkirk by the North Sean and (2) Weymouth station symmetrically with
611 respect to Cherbourg.
612 The French tide gauges are operated and maintained by the National French Center of
613 Oceanographic Data (SHOM) while the Britannic tide gauges are operated by the British
614 Oceanographic Data Center. All stations are referenced to the hydrographic zero level; they
615 provide time-series of hourly observations measurements until 2018.
616 Available data are summarized as the following: Brest (168 years between 1850 and 2018);
617 Cherbourg and Dunkirk (54 years between 1964 and 2018); Dover (53 years between 1963 and
618 2018); Weymouth (28 years between 1990 and 2018).
619 The hourly measurements suffer from some gaps of daily length distributed along the time-
620 series. These gaps have been processed by the hybrid model for filling gaps developed by Turki
621 et al. (2015b) by using the SLP as covariate in ARMA methods and the memory effects of the
622 previous distribution of surges to estimate the missing values and fill the gaps. This model has
623 been used in the recent works of Turki et al., (2019; 2020).
624 The large-scale atmospheric circulations are represented in this work by four different climate
625 indices which are considered as fundamental drivers in the Atlantic regions (Massei et al.,

2017; Turki el al., 2019; 2020): the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the Zonal Wind (ZW) component extracted at 850hPa, and the Sea-Level Pressure (SLP).

Monthly time-series of climate indices have been provided by the NCEP-NCAR Reanalysis fields (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html) until 2017. The different indices have been extracted during the same period of the sea-level observations at the four stations Cherbourg, Dunkirk, Dover and Weymouth. For the longest timeseries of Brest (1850 - 2018), the use of climate indices has been limited according to their initial date availability (AMO: 1880 – 2017; NAO: 1865-2017; SLP: 1948-2017; ZW: 1865-2017).

3. Methodological Approach

2. 1 Extraction of residual sea level: 'surges'

The total sea-level height, resulting from the astronomical and the meteorological processes, exhibits a temporal non-stationarity which is explained by a combination of the effects of the long-term trends in the mean sea level, the modulation by the deterministic tidal component and the stochastic signal of surges, and the interactions between tides and surges. The occurrence of extreme sea levels is controlled by periods of high astronomically generated tides, in particular at inter-annual scales when two phenomena of precession cause systematic variation of high tides. The modulation of the tides contributes to the enhanced risk of coastal

flooding. Therefore, the separation between tidal and non-tidal signals is an important task in any analysis of sea-level time-series. By the hypothesis of independence between the astronomical tides and the stochastic residual of surges, the nonlinear relationship between the tidal modulation and surges is not considered in the present analysis. Using the classical harmonic analysis, the tidal component has been modelled as the sum of a finite set of sinusoids at specific frequencies to determine the determinist phase/ amplitude of each sinusoid and predict the astronomical component of tides. In order to obtain a quantitative assessment of the non-tidal contribution in storminess changes, technical methods based on MATLAB t-tide package have been applied to the seal level measurements, demodulated from long-term components (e.g. mean sea level, vertical local movement), for estimating year-by-year tidal constituents. A year-by-year tidal simulation (Shaw and Tsimplis, 2010) has been applied to the sea-level time-series to determine the amplitude and the phase of tidal modulations using harmonic analysis fitted to 18.61-, 9.305-, 8.85-, and 4.425-year sinusoidal signals (Pugh, 1987). The radiational components have been also considered for the extraction of the stochastic component of surges (Williams et al., 2018).

3.2 Wavelet spectral analysis

The Continuous Wavelet Transform CWT is generally used for data analysis in hydrology, geophysics, and environmental sciences (Labat, 2005; Sang, 2013; Torrence and Compo, 1998). This technique produces the timescale with the means of the Fourier transform contour diagram on which the time is indicated on the x-axis, the timescale (period,) on the y-axis, and the variance (power) on the z-axis.

Then, a wavelet multiresolution analysis has been used to decompose the signal of monthly extreme surges into different internal components corresponding to different timescales. This decomposition consists on applying a series of iterative filtering to the signal by the use of low-pass and high-pass filters able to produce the spectral components describing the total signal. More details are presented in the recent works of Massei et al. (2017) and Turki et al., (2019). In summary, the total signal has been separated into a relatively small number of wavelet components from high to low frequencies that altogether explains the variability of the signal; this will be illustrated later using the hourly measurements and the monthly maxima of surges.

The wavelet coherence has been calculated to investigate the relationship between the extreme surges and the climate oscillations by identifying the timescales where the two timeseries co-vary, even if they do not display high power. Here, a significance test has been implemented by the use of a Monte Carlo analysis based on an autocorrelation function of two timeseries (Grinsted et al., 2004).

3. 3 Stationary and Nonstationary extreme value model

Finally, and with the aim of addressing the nonstationary behaviour of extreme surges, the monthly maxima of the surges have been calculated and decomposed with the multiresolution analysis. Then, a nonstationary extreme value analysis based on the GEV distribution with

687 time-dependent parameters (Coles, 2001) has been implemented to model the series of the
688 monthly maxima surges. There are several GEV families which depend on the shape parameter,
689 e.g. Weibull ($\varepsilon < 0$), Gumbel ($\varepsilon = 0$), and Fréchet ($\varepsilon > 0$). The three parameters of the GEV (i.e.
690 location μ, scale ψ, shape ε) are estimated by the maximum likelihood function.

691 The nonstationary effect was considered by incorporating the selected climate indices (NAO,
692 AMO, ZW, and SLP) into the parametrization of the GEV models. Akaike Information
693 Criterion (AIC) has been used to select the most appropriate probability function models. The
694 methods of maximum likelihood were used for the estimation of the distribution's parameters.
695 The approach used considers the location (μ), the scale (ψ), and the shape (ε) parameters with
696 relevant covariates, which are described by a selected climate index:

697 $$\mu(t) = \beta_{0,\mu} + \beta_{1,\mu} Y_1 + \cdots + \beta_{n,\mu} Y_n \quad (1)$$

698 $$\psi(t) = \beta_{0,\psi} + \beta_{1,\psi} Y_1 + \cdots + \beta_{n,\psi} Y_n \quad (2)$$

699 $$\varepsilon(t) = \beta_{0,\varepsilon} + \beta_{1,\varepsilon} Y_1 + \cdots + \beta_{n,\varepsilon} Y_n \quad (3)$$

700 Where $\beta 0$, $\beta 1$,…, βn are the coefficients, and Yi is the covariate represented by the climate
701 index. For each spectral component, only one climate index can be used to be introduced into
702 the parameters μ, ψ, and ε of the nonstationary GEV model (into one of them, into two of them
703 or into the three parameters).

With the aim of optimizing the best use of the most appropriate climate index (detailed in section 3.4) into the different GEV parameters, a series of sensitivity analyses were implemented for each timescale. The AIC measures the goodness of the fitting of the model (Akaike, 1973) to the relation AIC =-2l+2K; where l is the log-likelihood value estimated for the fitted model, and K is the number of the model parameters. Higher ranked models should result from lower AIC scores.

The non-stationary return levels and return-periods have been calculated using Bayesian inference, implemented in the Non-stationary Extreme Value Analysis (NEVA) software R-package. The Confidence intervals for the return level estimates have been calculated by the use of the method of delta (Coles, 2001).

3. 4 Determination of the most appropriate climate oscillation connected to each timescale extreme surges for GEV models

As suggested previously, the main hypothesis presented in this research is that effects of the physical mechanisms on the extreme surges vary according to the timescale and each scale should be related to a given climate oscillation.

This hypothesis has been investigated by two approaches:

(1) a spectral approach based on the use of wavelet techniques (wavelet multiresolution and wavelet coherence as detailed in section 3.2) for optimizing the physical relationship between the climate index and the extreme surges at each timescale. Here, a bootstrap approach has been applied to assess the statistical significance of the correlation between the spectral

component of the extreme surges and the climate oscillation at each timescale. By resampling the timeseries 10.000 times, 95% confidence intervals have been considered to extract the best climate information fitting the extreme surges (Villarini et al., 2009).

Here, the confidence intervals (CI) have been calculated by the bootstrap technique by simulating the monthly maxima of surges (spectral component) from the climate index (spectral component) at each timescale (new samples with a size of 1000). When the original surges have been fitted to the simulated ones, 95% confidence intervals for the maximum likelihood estimates have been calculated.

(2) a Bayesian estimation has been used to make inferences from the Likelihood function. The reason behind the choice of this approach is overcoming the limitation of short time-series with small size, the case of Weymouth station where the measurements covers the period from 1991 and 2018. A technique of Markov Chain Monte Carlo (MCMC), implemented in the evbayes package within R software, has been used basing on multiple simulations (the number of simulations is varying as a function of the length of the timeseries).

For each spectral component, a sample of 100.000 simulations has been modelled by GEV using a given climate index. The upper and lower quantiles of the posterior probability distribution for the parameters of the MCMC sample are taken. The goodness of fit has been taken as a function of the values of the upper and the lower quantiles; best results have been considered when these values are higher than 92.5% and lower than 5.2%, respectively.

4. Multi-timescale variability of extreme surges

The variability of the monthly extreme surges along the English Channel coasts has been investigated using the continuous wavelet transform (CWT). In the spectrum of Figure 2, the colour scale represents an increasing power (variance) from red to blue and pink. The CWT

749 diagrams highlight the existence of several scales for all sites with different ranges of
750 frequencies: the interannual scales of ~ 1.5-yr, ~ 2-4-yr, ~ 5-8-yr and the interdecadal scale of
751 ~ 12-16-yr.

752 The variability of surges is clearly dominated by the interannual frequencies (~ 1.5-yr, ~ 2-4-
753 yr, ~ 5-8-yr) explaining a mean variance between 32% and 25% of the total energy (Table 1).
754 In Dover and Weymouth, the low frequencies of ~ 2-4-yr are well-structured with a mean
755 explained variance of 9.5% while it is of 7% for ~ 5-8-yr. These percentages decrease slightly
756 for the French sites to 8% and 5%, respectively. At ~ 1.5-yr, the explained variance is higher
757 than 16% and 13% respectively in Britannic and French coasts. The interdecadal frequency of
758 ~ 12-16-yr varies between 2% and 4% from the total signal. This frequency is not observed in
759 the shortest timeseries of Weymouth (Table 1).
760 The interannual variability (time-scales higher than ~1 year) seems to be highly represented in
761 the monthly extrema CWT (Figure 2). It's not the case for the monthly mean surges (Figure
762 3.a) where most power spectrum is concentrated on the annual cycle with an explained variance
763 higher than 50%.

764 The time-dependent PDF of the monthly mean and maximum surges over a period of 10 years,
765 for illustration purpose, is displayed in Figure 3.b. The ~1-yr component of monthly mean

766 surges is largely manifested with a pronounced variation of the Gaussian curves in time; such
767 variations take wavelengths of approximately ~2-yr and ~4-yr. This result exhibits that the
768 interannual frequencies of ~2-yr and ~4-yr are modulated within the annual mode for the mean
769 surges while they are implicitly quantified for the monthly maxima.

770 Results have been explored to investigate the nonstationary dynamics of surges at different
771 timescales. We have applied the wavelet multiresolution decomposition of monthly extrema
772 for each site. The process has resulted in the separation of several components with different
773 time-scales. Only the wavelet components, with have been considered in this work. In this
774 research, we are interested in the time-scales higher than 1 year, i.e. traduced by three
775 interannual scales (~ 1.5-yr, ~ 2-4-yr, and ~ 5-8-yr) and a interdecadal scale of ~ 12-16-yr. We
776 focused only on the interannual and the interdecadal scales whose fluctuations correspond to
777 the oscillation periods less than half the length of the record and exhibit a high-energy
778 contribution on the variance of the total signal. The lowest frequency, corresponding to ~ 12-
779 16-yr is easily calculated from the longest record of Brest.

780 Figure 4 shows a series of oscillatory components of surges from interannual to interdecadal
781 scales, not easily quantified by a simple visual inspection of the signal. High similarities
782 between the different sites have been highly observed for the interannual and the interdecadal

783 scales of ~ 5-8-yr and ~12-16-yr while they are less pronounced at the small scales of ~ 1.5-yr.
784 At this timescale, the differences in the extreme surges can be explained by local physical
785 phenomena controlling their dynamics. Such processes are mainly induced by combining the
786 effects of meteorological and oceanographic forces including changes in atmospheric pressures
787 and wind velocities in shallow water areas. Beyond ~ 1.5-yr, the variability of extreme surges
788 at larger scales seems to be quite similar in terms of frequency and amplitude for the five sites.
789 Such large variability reveals the physical effects of a global contribution related to climate
790 oscillations. The extent of the large-scale oscillations is not strictly similar and changes
791 according to the timescale variability since the dynamics of surges is not necessarily related to
792 the same type of atmospheric circulation process. This relationship will be addressed later in
793 the second part of this section.
794 Here, the multiscale variability of extremes has been investigated from the spectral components
795 of surges along the English Channel coasts. This signal has been linearly extracted from the
796 total sea level, provided by tide gauges, by the use of the classical harmonic analysis and thanks
797 to the assumption that the water level is the sum of the mean sea level, tides, and surges. This
798 assumption approximates the quantification of both components in the English Channel where
799 the significant tide-surge interactions (Tomassin & Pirazzoli, 2008) and the effects of the sea-

level rise on tides and surges are important (e.g. Idier et al., 2017). Neglecting this nonlinear interaction between the surges, tides, and the sea-level rise suggests some uncertainties in the estimation of the high frequencies of the spectral components between daily and monthly scales, which is not the focus of the present work where the interannual and the interdecadal scales are investigated.

Similar interannual timescales have been observed along the French coasts of Dunkirk, Le Havre and Cherbourg in Turki et al., (2020) works where the intermonthly and the interannual variability of 48-year hourly surges has been investigated. They have demonstrated that the timescales smaller than ~ 1.5-yr are differently manifested between the different sites. These differences have been associated to the local variability of surges induced by combining the effects of meteorological and oceanographic forces including changes in atmospheric pressures and wind velocities in shallow water areas. As demonstrated in Turki et al. (2020) works, the mean explained variance of the interannual fluctuations (~ 1.5-yr, ~ 2-4-yr, and ~ 5-8-yr) is around 25% of the total surges along the French coasts (Table 1). This value is higher than 32% in Weymouth and Dover while the explained variance of the interdecadal scales (~ 12-16-yr) is also more important with 3.5% (compared to 2% for the French coasts).

The interdecadal variability (~ 12-16-yr) of extreme surges have been evidenced by Turki et al., (2019) in the Seine bay (NW France). Strong physical relations have been exhibited between the interdecadal time of ~ 12-16-yr and the exceptional stormy events produced with surges higher than 10-year return period level. The connections between the low-frequency components and the historical record of the exceptional events suggested that storms would occur differently according to a series of physical processes oscillating at multi-timescales; these processes control their frequency and their intensity (Turki el al., 2019).

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Accordingly, the multiscale variability of extreme surges exhibits a nonstationary behaviour modulated by a non-linear interaction between the different interannual and the interdecadal timescales. Then, assessing the effect of the nonstationary behaviour at different timescales is important for improving the estimation of extreme values and the projection of storm surges.

5. Large-scale climate North-Atlantic oscillations and their link to extreme surges in the English Channel

In this part, a new hybrid approach combining the spectral analysis and the nonstationary GEV models has been used to investigate the connection between the multi-timescale variability of local surges and the large-scale climate North Atlantic oscillations.

As proposed by Turki et al. (2019; 2020), the hypothesis used in the present work is that the multi-timescale variability of the local extreme surges should be strongly related to different climate teleconnections induced by a complex contribution of many physical mechanisms. This non-linear relationship varies according to each timescale which depends on a specific large-scale oscillation of atmospheric circulation.

5.1 To what extent would large-scale climate oscillations link extreme surges?

The wavelet coherence (WC) diagrams between the monthly maxima of surges and the different climate indices of SLP, ZW, NAO, AMO, introduced previously as the main atmospheric circulation within the English Channel, are illustrated respectively in Figures 5, 6, 7 and 8. Results provided by these diagrams highlight:

1. The connection between the climate oscillations and the extreme surges is manifested differently as a function of the timescale. From a visual inspection of the different spectra provided WC, the most significant correlations of extreme surges have been

identified with SLP, ZW, NAO and AMO respectively at ~ 1.5-yr, ~ 2-4-yr, ~ 5-8-yr and ~ 12-16-yr.

2. Each timescale exhibits mainly strong links with its associated climate index (explained variance varying between 55% and 80%) and weak ones with other indices (explained variance varying between 15% and 5%). Table 2 summarizes the contribution of the different climate oscillations in the different interannual and interdecadal timescales of extreme surges. Here, mean values between the different sites are presented.

For example, SLP diagrams reveal significant relationships with ~ 1.5-yr surges (well-structured forms with high concentration of pink-blue colours in Figure 5); limited correlations, locally positioned in time, have been observed at ~ 2-4-yr and ~ 5-8-yr scales. ZW shows strong correlations with interannual surges at ~ 2-4-yr (blue to pink colour at this scale; Figure 6) and others correlations at smaller and larger timescales of ~ 1.5-yr and ~ 5-8-yr, respectively. Similarly, NAO presents high links with ~ 5-8-yr surges and small relations with ~ 2-4-yr and ~ 1.5-yr (Figure 7).

The ~ 1.5-yr scale highlights strong correlations with SLP with an explained variance of 75%; 25% of this scale should be explained by the influence of other climate oscillations (basically

ZW and NAO with a mean explained variance of 10% and 6%, respectively; Table 2) and the combining effects of local driven forcing induced by winds and waves.

65% of ~ 2-4-yr scale is correlated with ZW while 5% and 12% is explained by the effect of NAO and SLP, respectively. The effects of NAO on the ~ 5-8-yr vary between 55% and 65%; minor influence at this scale has been observed with SLP and ZW explaining a mean variance of 13%. The interannual scales of surges are slightly influenced by AMO oscillations with low values of variance lower than 1% (Table 2).

At interdecadal scales of ~ 12-16-yr, the extreme surges are mainly controlled by the AMO oscillations with a mean explained variance of 80% while the effects of NAO is limited to 10%. Figure 9 displays the spectral components of the four climate oscillations, provided by a multi-resolution analysis, together with the spectral components extracted from the extreme surges (Figure 4) with the aim to quantify the different connections between both variables at the interannual and the interdecadal timescales.

For each timescale, a bootstrap approach has been applied to assess the statistical significance of the correlation between the spectral component of the extreme surges and the climate oscillation. By resampling the timeseries 10.000 times, 95% confidence intervals have been considered to extract the best climate information fitting the extreme surges (Villarini et al., 2009).

885 The best correlation of each surge component (i.e. ~ 1.5-yr, ~ 2-4-yr, ~ 5-8-yr and ~ 12-16-yr)
886 with the suitable climate index (i.e. SLP, ZW, NAO and AMO) is illustrated in Figure 9.
887 The interannual and the interdecadal variability of extreme surges and their multiscale
888 connection with the climate oscillations highlight the nonlinear relationship between large- and
889 local- scales.

890 Therefore, the interannual and the interdecadal extreme surges have proven to be strongly
891 related to different composites of oscillating atmospheric patterns. Such composites seem to be
892 not necessarily similar for the different timescales. The use of a multiresolution approach to
893 investigate the dynamics of the extreme surges into the downscaling studies proves to be useful
894 for assessing the nonstationary dynamics of the local extreme surges and their nonlinear
895 interactions with the large-scale physical mechanisms related to climate oscillations.

896 Investigating the complex relationships between the climate oscillations and the multi-
897 timescale surges has exhibited a multimodel climate ensemble that should be used to better
898 understand this complexity.

899 The interannual connections between the local hydrodynamics and the climate variability have
900 been investigated in numerous previous works focused on the atmospheric circulation with

different related mechanisms (e.g., Feliks et al., 2011; Lopez-Parages et al. 2012; Zampieri et al., 2017). As demonstrated by the recent works of Turki et al. (2019, 2020), the effects of SLP oscillations on the ~ 1.5-yr variability of extreme surges are described by dipolar patterns of high-low pressures with a series of anomalies which are probably induced by some physical mechanisms linked to the North-Atlantic and ocean/atmospheric circulation oscillating at the same timescale.

The SLP fields combined with the baroclinic instability of wind stress have been related to the Gulf Stream path as given by NCEP reanalysis (Frankignoul et al., 2011); the dominant signal is a northward (southward) displacement of the Gulf Stream when the NAO reaches positive (negative) extrema. Daily mean SLP fields have been used by Zampieri et al. (2017) to analyse the influence of the Atlantic sea temperature variability on the day-by-day sequence of large-scale atmospheric circulation patterns over the Euro-Atlantic region. They have associated the significant changes in certain weather regime frequencies to the phase shifts of the AMO. For hydrological applications, several works have investigated the multiscale relationships between the local hydrological changes and the climate variability. Lavers et al. (2010) associated the 7.2-yr timescales to SLP patterns which are not exactly reminiscent of the NAO and define centers of action which are shifted to the North.

Regarding the ZW (u850), results have shown its correlation with the interannual scales of ~2-4-yr extreme surges as suggested also in the recent findings of Turki et al. (2020). Its influence has been proven also at smaller (~1.5-yr) and larger scales (5-8-yr). Additionally, to extreme surges, the interaction between the ZW and the temperature at different timescales has been highlighted in some previous researches (e.g., Andrade et al., 2012; Seager et al. 2003; Woodworth et al., 2007). Along UK and Northern English Channel coats, Changes in trends of extreme waters and storm surges have been explained by variations of energy pressure and ZW variability additional to thermosteric fluctuations linked to NAO (Woodworth et al., 2007).

Andrade et al. (2012) have used the component of ZW at 850 hPa to investigate the positive and the negative phases of the extreme temperatures in Europe and their occurrence in relation with the large-scale atmospheric circulation. They suggested that both phases are commonly connected to strong large-scale changes in zonal and meridional transports of heat and moisture, resulting in changes in the temperature patterns over western and central Europe (Corte-Real et al., 1995; Trigo et al., 2002). The physical connections between ZW and the extreme events from 11 Global Climate Model runs have been demonstrated by the studies from Mizuta (2012) and Zappa et al (2013); they have suggested the complex relationship between the climate oscillation and the jet stream activity. They have found a slight increase

935 in the frequency and strength of the storms over the central Europe and decreases in the number
936 of the storms over the Norwegian and Mediterranean seas.
937 The NAO is considered as an influencing climate driver for the large-scale atmospheric
938 circulation, as suggested by other researches (e.g. Marcos et al., 2009; Philips et al., 2013).
939 The existence of long-term oscillations originating from large-scale climate variability and thus
940 controlling the interannual extreme surges has been highlighted from investigating the low
941 frequencies of the sea levels along the English Channel. This is in agreements with the results
942 recently demonstrated by Turki et al. (2020) and the present finding exhibiting the strong links
943 between NAO oscillations and the ~ 5-8-yr extreme surges along the English Channel coasts.
944 The physical mechanisms related to the effects of the continuous changes in NAO patterns on
945 the sea-level variability have been addressed in several studies (e.g., Marcos et al., 2005;
946 Tsimplis et al., 1994). At the interannual scales, the key role of NAO on the sea-level variability
947 has been explained by some previous works: Philips et al. (2013) investigated the influence of
948 the NAO on the mean and the maximum extreme sea levels in the Bristol Channel/Severn
949 Estuary. They have demonstrated that when high NAO winters increase in the positive phase,
950 wind speeds also escalate while increasing the negative NAO warmers results in low wind
951 speeds. Then, the correlation between the low/high extreme surges and the NAO in the Atlantic

952 has demonstrated a proportionality between NAO values and the augmentation in the winter
953 storms. Feliks et al. (2011) defined significant oscillatory timescales of ~ 2.8-yr, ~ 4.2-yr, and
954 ~ 5.8-yr from both observed NAO index and NAO atmospheric marine boundary layer
955 simulations forced with SST; they have suggested that the atmospheric oscillatory modes
956 should be induced by the Gulf Stream oceanic front.

957 Strong correlations between the monthly extreme surges and the AMO oscillations have been
958 identified at the timescale of 12-16-yr (Figure 8 and Figure 9; in particular for Brest). Since the
959 period of 1990's, the AMO and the extreme surges oscillate in opposition of phase. This shift
960 should be explained by a substantial change in European climate manifested by cold wet and
961 hot dry summers in the northern and the southern Europe, respectively; as discussed by Sutton
962 and Dong (2012). They have demonstrated that the patterns, identified from the European
963 climate change around 1990's, are synchronised with changes related to the North Atlantic
964 Ocean.

965 Other weak links with the AMO have been identified at the interannual timescales of ~5-8-yr.
966 along the studied sites. In agreement of previous works (e.g., Enfield et al., 2001; Zampieri et
967 al., 2013; 2017), the effects of the AMO oscillations are mainly manifested at the interannual
968 timescales to control the variability of hydrological (e.g. rainfall) and oceanographic (e.g.
969 surges) variables. Generally, the climate oscillations of AMO are associated to the SST
970 variability with a time cyclicity of about 65-70-years (e.g. Delworth and Mann, 2000; Enfield
971 et al., 2001). During the warming periods of the 1990's, the AMO shifts from the negative to
972 the positive phases in the Northern Hemisphere corresponding to cold and warm periods (e.g.

973 Gastineau et al., 2012; Zhang et al., 2013). This shift can be responsible on changes in the
974 hydrodynamic conditions (e.g. Zampieri et al., 2013).

975 The influence of the AMO oceanic low frequencies in the modulation of the mechanisms of
976 the atmospheric teleconnections at the interannual timescales has been investigated in many
977 previous works (e.g Enfield et al. 2001). At decadal timescales, the existing relationships
978 between the winter NAO and the AMO variability is more complex (e.g. Peings and
979 Magnusdottir, 2014).

980 The effects of the AMO-driven climate variability on the seasonal weather patterns have been
981 investigated by Zampieri et al. (2017) in Europe and the Mediterranean. They have
982 demonstrated significant changes in the frequencies of weather regimes involved by the AMO
983 shifts which are in phase with seasonal surface pressure and temperature anomalies. Such
984 regimes, produced in Spring and Summer periods, are differently manifested in Europe with
985 anomalous cold conditions over Western Europe (Cassou et al., 2005; Zampieri et al., 2017).

986 In summary, four atmospheric oscillations have proven to be significantly linked to the
987 interannual and interdecadal variability of extreme surges. This physical link varies according
988 to the timescale exhibiting a nonlinear interaction of the same oscillations with other scales.
989 Such nonlinear behavior depends on the dynamics of the different sequences of the atmospheric
990 and water vapour transport patterns during the month prior to the sea-level observations (e.g.
991 Lavers et al., 2015). As suggested by Turki et al. (2020), the atmospheric circulation acts as a
992 regulator controlling the multiscale variability of extreme surges with a nonlinear connection
993 between the large-scale atmospheric circulation and the local scale hydrodynamics. This multi-

timescale dependence between the local extreme dynamics and the internal modes of climate oscillations is still under debate. Understanding these physical links, even their complexities, are useful to improve the estimation of the extreme values in coastal environments; which is the objective of the next part.

5.2 Nonstationary modelling of extreme surges

In this part, stationary and nonstationary extreme value analyses based on GEV distribution with time-dependent parameters (Coles, 2001) have been implemented to model separately the different spectral components of extreme surges. Four GEV stationary (GEV0) and nonstationary (GEV1, GEV2 and GEV3) models have been applied to each timescale and each site. The GEV distribution uses the maximum likelihood method by parametrizing the location, scale, and shape of the model. We have used the 'trust region reflective algorithm' for maximizing the log-likelihood function (Coleman and Li, 1996).

The connections between the climate oscillations and the monthly maxima at the different timescales (Figure 9)., presented previously (section 5.1), have been explored as a first hypothesis for the implementation of the nonstationary GEV models. Indeed, multiple simulations of Markov Chain Monte Carlo (MCMC) techniques based on Bayesian approaches have been employed for extreme surge components (i.e. ~ 1.5-yr, ~ 2-4-yr, ~ 5-8-yr and ~ 12-

16-yr provided by the multiresolution wavelet decomposition) to identify the best covariates of climate oscillation for parametrizing the nonstationary GEV models. The most of simulations has mainly supported the results outlined in the previous section: the ~ 1.5-yr of SLP, ~ 2-4-yr of ZW, ~ 5-8-yr of NAO and ~ 12-16-yr of AMO oscillations are considered as the best covariates for modelling respectively the ~ 1.5-yr, ~ 2-4-yr, ~ 5-8-yr and ~ 12-16-yr of monthly extreme surges.

Once the climate covariate has been selected for each timescale, three nonstationary models have been used by introducing the climate information as a covariate into: (1) the location parameter (GEV1); (2) both location and scale parameters (GEV2); (3) all location, scale and shape parameters (GEV3). The structure of the most appropriate nonstationary GEV distribution has been selected by choosing the most adequate parametrization that minimizes the Akaike information criterion (Akaike, 1974). The goodness of fit for each model has been checked through the visual inspection of the quantile-quantile (Q-Q) plots (Figure 10); these plots compare the empirical quantiles against the quantiles of the fitted model. Any substantial departure from the diagonal indicates inadequacy of the GEV model.

1027 At the interannual scales and for all sites, results provided by the nonstationary GEV1-3 reveal
1028 a better performance (the lowest values of AIC) of extreme estimation compared to the
1029 stationary models of GEV0 and give the most appropriate distributions by the use of the climate
1030 large-scale covariates for specific oscillating components of extreme surges. Nevertheless, this
1031 improvement from the stationary to the nonstationary models has not been clearly observed for
1032 the interdecadal scales where the extreme estimation, provided by the different GEV models,
1033 is very similar (Table 3). The lowest values of AIC have been shown by GEV3 for ~1.5-yr,
1034 GEV2 for ~2-4-yr and GEV1 for ~5-8-yr (Table 4). The Q-Q plots for the all timescales of all
1035 timescales of the monthly maxima in Brest are illustrated in Figure 10; they confirm the
1036 suitability of the selected models.
1037 Accordingly, the nonstationary GEV models have exhibited high improvements at the
1038 interannual scales where the AIC scores have significantly decreased by introducing the
1039 climate information into the parametrization of the model. Such consideration varies as a
1040 function of the spectral components, it concerns all parameters for the smallest scale of ~1.5-
1041 yr, both location and scale parameters for ~2-4-yr and only the location parameter for largest
1042 scale of ~5-8-yr.

1043 Then, the large-scale oscillations introduced for the implementation of GEV parameters depend
1044 on the time scale for all sites exhibiting a high nonstationary behaviour of the small interannual
1045 scales (~1.5-yr) which decreases at the large interannual scales (~5-8-yr) and get non-
1046 significant at the interdecadal scales (~ 12-16-yr).
1047 The use of the time-varying GEV parameters at the interannual scales (~ 1.5-yr and ~ 2-4-yr)
1048 exhibits the relationship between the mode and the standard deviation of the GEV distributions
1049 associated with the location and the scale parameters, respectively.
1050 The different implications of both parameters for estimating the interannual extreme surges
1051 reveal cyclic variations and timescale modulations related to the large-scale climate
1052 oscillations. As documented in the previous works (e.g., Menendez et al., 2009; Masina and
1053 Lamberti., 2013), the location and the scale parameters used for improving the nonstationary
1054 estimation of the extreme water levels highlight a series of annual and semi-annual evolutions.
1055 They have reported that the seasonal cycles of the location parameter are related to tow maxima
1056 of water levels, in early March and September produced during equinoctial spring tides, while
1057 the seasonal cycles of the scale parameter are associated to an increase of storms during wintry
1058 episodes. Here, we focus on the stochastic signal of surges at scales larger than one year. The
1059 SLP and the ZW frequencies, introduced in the location and the scale parameters of

nonstationary GEV models, determine an enhancement in the prediction of the interannual scales.

The shape parameter, implied for the estimation of the ~1.5-yr extreme surges, derives from its determination of the upper tail distribution behaviour. The time-varying shape parameter uses the ~1.5-yr SLP exhibiting altering negative and positive oscillations.

Despite its critical significance, the shape GEV parameter has revealed its relationships with basin attributes in hydrological applications and regional flood frequency analysis (e.g., Tyralis et al., 2019). The dependence of the shape parameter on the climate oscillations has been demonstrated in several extreme frameworks related to hydrological and oceanographic applications (e.g., Menendez et al., 2009; Masina et al., 2013; Turki et al., 2020). Regarding the stationarity of the surge timescale, the ~12-16-yr window sliding matches have been quantified in the previous part exhibiting a substantial cyclic variability consequence of an altering periods of positive and negative correlations. The modelling of the interdecadal extreme surges involves a stationary behavior of the ~12-16-yr.

Th stationary behavior of low frequencies has been outlined by Zampieri et al. (2017). They have demonstrated a stationary trend of the SST anomalies associated with the AMO over the Euro-Atlantic region. According to their works, the low-frequency variability of the European Climate is influenced by the AMO shift induced by the phase opposition between the negative NAO distribution and the Atlantic patterns.

Here, the effects of AMO on ~12-16-yr of extreme surges have been largely observed in Figure 9 for the longer timeseries Brest where the lower frequencies could be easily identified.

At this timescale, the AIC values given by the different GEV models are pretty close and the difference between the distributions are not statistically significant. The stationary behavior of ~12-16-yr surges should be more investigated from additional applications in light of the available sea level measurements covering a long period of time, a relevant parameter to characterize the uncertainties in extreme value statistical modeling of flood hazards.

The return levels of the multiscale extreme surges, provided by the best GEV models (Table 3), have been simulated. The example of Brest is illustrated in Figure 10.b for the interannual (nonstationary GEV models) and the interdecadal (GEV stationary model) scales. The 95% confidence interval is also plotted in this graph through a dashed black line. Accordingly, the use of GEV distribution with time-dependent parameters for each timescale should improve the evaluation of the return values and reduce the uncertainty of the quantile estimates.

Similar works have been carried out by Wahls and Chambers (2016) to investigate the multidecadal variations in extreme sea levels with the large-scale climate variability. By the use of climate indices on nearby atmospheric/oceanic variables (winds, pressure, sea surface temperature) as covariates in a quasi-nonstationary extreme value analysis, the range of change in the 100-year return water levels has been significantly reduced over time, turning a nonstationary process into a stationary one.

As suggested by Wong (2018), including a wider range of physical process information and considering nonstationary behaviour can better enable modelling efforts to inform coastal risk management. In his work, he has developed a new approach to integrate stationary and nonstationary statistical models and demonstrated that the choice of covariate timeseries should affect the projected flood hazards. By developing a nonstationary storm surge statistical model with the use of multiple covariate timeseries (global mean temperature, sea level, the North

Atlantic Oscillation index and time) in Norfolk and Virginia, he has shown that a storm surge model raises the projected 100-year storm surge return level by up to 23 cm relative to a stationary model or one that employs a single covariate timeseries.

This study has expanded the previous works of Turki et al. (2019; 2020) upon a new approach combining spectral and probabilistic methods to integrate multiple streams of information related to climate teleconnections. Indeed, each timescale has been simulated separately with the nonstationary GEV models and expressed as a function of the most suitable climate index improving its fitting. The estimation of the total signal of surges should be determined by combining the developed nonstationary GEV models used for the different timescales.

These results should support the hypothesis introduced at the beginning of the present work suggesting that: (i) the extreme surges should depend on different timescales; (ii) each timescale should be related to a specific large-scale oscillation.

The finding is in agreement with the previous works of Lee et al. (2017) and Wang et al. (2018) highlighting the importance of a careful consideration when complex physical mechanisms of different climate indices are included into model structures for estimating extreme surges. Indeed, this work provides a guidance on incorporating nonstationary processes of large-scale oscillations to different spectral components informed by the wavelet techniques, the Bayesian approaches and the GEV model probabilities.

The primary contribution of the present research is to present a new approach for: (1) investigating the multi-timescale variability of the nonstationary extreme surges; (2) identifying their multi-connection with climate oscillations according to the timescale and (3) resolve in part the problems of uncertainty of most appropriate climate to use as covariate for GEV models at each timescale. However, additional models (e.g. significance tests and sensitivity analyses and modelling uncertainties) and application sites (e.g. Mediterranean and

pacific ones controlled by other climate oscillations) are required to expand the developed approach.

Also, generating a final robust stochastic model useful for projecting storm surge return levels and assessing the flood risk management requires further efforts to build on the potentially advantageous approach presented here by integrating the GEV models associated with the different timescales through the use of mathematical methods.

6. Summary and Concluding remarks

The dynamics of extreme surges together with the large-scale climate oscillations have been investigated by the use of hybrid methodological approach combining spectral analyses and nonstationary GEV models. Results have demonstrated that the interannual variability of extreme surges (~ 1.5-yr, ~2-4-yr and 5-8-yr) is around 25% for the French coasts and higher than 32% for the Britannic coasts; the interdecadal variability (~12-16-yr) varies between 2% and 4%. The fluctuations of extreme surges at ~1.5-yr are differently manifested between the different sites of the English Channel exhibiting a local variability of surges induced by the effects of meteorological and oceanographic forces including changes in atmospheric pressures and wind velocities in shallow water areas. Similar fluctuations have been observed at larger scales of the interannual and the interdecadal variability. Changes in extreme surges (~1.5-yr, ~2-4-yr, ~5-8-yr and ~12-16-yr) have been proven to be significantly linked to atmospheric

1151 oscillations (SLP, ZW, NAO and AMO, respectively) according to the timescale with a
1152 nonlinear interaction between different oscillations at the same scale. This exhibits the complex
1153 physical mechanisms of the global atmospheric circulation acting as a regulator and controlling
1154 the local variability of extreme surges at different timescales. The connections between the
1155 multiscale extreme surges and the internal modes of climate oscillations have been explored to
1156 improve the estimation of extreme values by the use of nonstationary GEV models. The
1157 simulated extreme surges have highlighted that introducing the climate oscillations for the
1158 implementation of GEV parameters depends on the timescale for all sites; a high nonstationary
1159 behaviour of the small interannual scales (~1.5-yr) decreases at the larger scales (~5-8-yr) and
1160 seems to be non-significant at the interdecadal scales (~ 12-16-yr).

1161 The conclusion of this research suggests that the physical mechanisms driven by the
1162 atmospheric circulation, including the Gulf Stream gradients, play a key role in coastal extreme
1163 surges. Establishing a strong connection of the large-scale climate oscillations with extreme
1164 surges and flooding risks improve the estimation of the return levels.

1165 This finding presents a handful of a new approach potentially useful as a first step forward for
1166 (1) understanding the physical relation of downscaling from the global climate patterns to the
1167 local extreme surges; (2) inferring the future projections of sea level change and extreme

events. Future work should build on this new approach to (1) improve the stochastic modelling of the multi-timescale extreme surges; (2) incorporate others climate mechanisms known to be important at local and regional scales for specific applications; (3) generate a robust tool for the storm surge projections and the flood risk assessments based on the different timescale models connected to their specific climate drivers.

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