Replies to comments by referees

Extreme significant wave height of tropical cyclone waves in the South China Sea

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Thank you for your comments on our manuscript entitled "Extreme significant wave height of tropical cyclone waves in the South China Sea" (Ref: nhess-2018-349). These comments are all valuable and very helpful for improving our paper. We appreciate that we have a chance to revise the manuscript as you suggested and to resubmit our manuscript after addressing all comments point by point. We hope that the improved manuscript will meet your approval.

The main corrections in the manuscript and responses to comments are shown as follows:

Referee #1

The manuscript "study of the threshold for the POT method ..." is scientifically interesting, in that it is explores methodologyies for extreme value analysis in presence of tropical cyclones, where the choice of too low thresholds can lead to excessively broad extreme tails, and to irreasonably high return values for high return periods.

However the quality of the manuscript could be improved a lot. First of all, the way the threshold is selected is unclear, and I don't understand many details of what the authors do. Sometimes the text is exceedingly technical, verbose and full of repetitions. Other times relevant aspects of the research are omitted or unclear. Furthermore, the quality of the English is far from optimal.

I would therefore suggest a careful review, that should substantially change the way the methodology is exposed. I would also suggest to have the manuscript copy-read by a motherlanguage English.

Response: Thank you for your evaluation of our manuscript. As suggested, some of the contents in the manuscript have been rewritten to improve the quality of the manuscript, and the threshold selection method is described clearly in detail. In addition, we have rephrased the paper to present ideas more concisely and strictly. To further improve the manuscript, proofreading and language editing have been completed by American Journal Experts.

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(1) the title is long and too technical. One has to read it a couple of times to understand the argument. Why not something simpler, like "extreme value analysis of tropical cyclone waves in the Southern Chinese Sea" ?

Response: As suggested, the title has been changed to "Extreme significant wave height of tropical cyclone waves in the South China Sea".

(2) lines 14-20 of the abstract: the authors could simply write "A 40-year (1975-2014) hindcast of tropical cyclone waves is used to study the extreme wave heights, employing a Generalized Pareto Distribution (GPD) approach". The rest are details that could be left in the discussion.

Response: As suggested, the contents of the corresponding lines have been simplified.

- See the manuscript P. 1, lines 13-15: "In this study, a 40-year (1975-2014) hindcast of tropical cyclone waves is used to analyse the extreme significant wave height, employing the peak over threshold (POT) method with the generalized Pareto distribution (GPD) model."

(3) end of the abstract, "initial sample": as far as I can understand, here and elsewhere for the authors the "initial sample" is what I would call the "sample", and for the authors the "sample" is what I would call the "peaks over threshold".

Response: As suggested, "initial sample" was renamed "sample", and "sample" was renamed "extreme sample" (i.e., peaks over threshold).

(4) page 4, line 18: in what way the return levels in AM are unreasonable? And why?

Response: As suggested, "the return levels in AM are unreasonable" was clearly described and explained in the manuscript.

- See the manuscript P. 3, lines 19-22; P. 4, lines 1-10: "Shao et al. (2018a) compared the annual maxima (AM) method (Tawn, 1988) with the POT method. The AM method is an easy sampling method that does not require additional work, as the method directly extracts the annual maximal significant wave height for extrapolation. However, the AM method has limitations in a fixed time window (i.e., one year), which cannot guarantee the independence and number of samples. The annual maximal significant wave height obtained from neighbouring years may originate from the same extreme wave; some maximal significant wave heights may be neglected (i.e., the annual maximal significant wave height may be smaller than some unselected maximal significant wave heights in other years), resulting in an insufficient number of samples, especially for a relatively long return period. In a tropical cyclone, the AM method's limitation is further exacerbated, even if the return period is close to the database size. The annual frequency, intensity and track of recorded tropical cyclones greatly vary, and corresponding waves have obvious differences. Shao et al. (2018a) found that the minimal sample may be much less than the maximal sample, and the minimal sample may be too small to represent the extreme wave (i.e., the minimal sample in the AM method is obviously smaller than the extreme sample in the POT method)."

(5) - page 5, line 4: .. which shows that it is possible to study the extreme significant wave height of tropical cyclones

Response: As suggested, the content in the corresponding line was rephrased.

- See the manuscript P. 5, lines 5-6: "Thus, it is possible to study the extreme significant wave height in a tropical cyclone."

(6) - page 5, lines 5-10: the meaning of these lines is rather unclear.

Response: As suggested, the contents in the corresponding lines were rewritten to clearly show our ideas.

- See the manuscript P. 5, lines 6-9: "To achieve the assessment, a 40-year (1975-2014) hindcasted significant wave height of tropical cyclone waves is employed as the initial database. Considering that the hindcast is independently simulated during the tropical cyclone recorded in the SCS, the maximal significant wave height of the tropical cyclone wave can be directly extracted as the sample when the tropical cyclone influences the wave at the targeted location."

(7) - page 5, line 7: peak significant wave height, maybe the "maximum significant wave height" would be better, as it is in both space and time.

Response: As suggested, “peak significant wave height” was renamed “maximal significant wave height”.

(8) - page 5, lines 18-19: the words "threshold selection method" are repeated twice in the same sentence (the authors here and elsewhere should avoid so many repetitions)

Response: As suggested, the contents in the corresponding lines were rephrased to avoid repetition. In addition, we rephrased the paper to present our ideas more concisely.

- See the manuscript P. 4, lines 15-18: “Based on this conclusion, Shao et al. (2018a) defined the largest threshold within the common stable threshold range as the suitable threshold, and Liang et al. (2019) proposed an Automated Threshold Selection Method based on the characteristic of Extrapolated significant wave heights (the acronym is ATSME).”

(9) - page 5, line 20, the acronym ATSME is not introduced.

Response: As suggested, the acronym ATSME was introduced.

- See the manuscript P. 4, lines 15-18: “Based on this conclusion, Shao et al. (2018a) defined the largest threshold within the common stable threshold range as the suitable threshold, and Liang et al. (2019) proposed an Automated Threshold Selection Method based on the characteristic of Extrapolated significant wave heights (the acronym is ATSME).”

(10) - page 6, lines 3-5: this is not necessarily true: one could use some automatic technique to decide when the r.l. is not changing.

Response: As suggested, the contents in the corresponding lines were deleted.

(11) - page 6, line 10: "the subjective definition still exists in the atsme". It is not entirely clear why.

Response: In the ATSME, the maximal threshold of the stable threshold range is used to extract the extreme sample. Considering that the selected threshold is within the stable threshold range, the influence of this definition is small for the return significant wave heights. As mentioned, the content in corresponding lines may mislead readers. Thus, we have deleted the corresponding contents.

(12) - page 6, lines 17-18: "in section 4 the sampling method is described".

Response: As suggested, the contents in the corresponding lines were rewritten.

- See the manuscript P. 5, line 16: “In Section 4, the sampling method is described.”

(13) - page 6, line 19: "section 5 discusses the characteristics of ..."

Response: As suggested, the content in the corresponding line was rewritten.

- See the manuscript P. 5, lines 16-17: “In Section 5, the characteristics of tropical cyclone waves are discussed.”

(14) - section 2: this is be the right place to summarize the technique used by the authors to estimate the threshold.

Response: As suggested, the technique used by the authors was summarized in Section 2.

- See the manuscript P. 6, Background.

(15) - page 9, line 2: from "nine-hundred" to "tropical cyclone" there is something wrong in this sentence

Response: As suggested, the content in the corresponding line was rewritten.

- See the manuscript P. 9, lines 10-11: “From 1975 to 2014, waves are simulated only during 974 independent tropical cyclones."

(16) - section 3.2, a figure with the position of the 22 locations would be useful

Response: As suggested, a figure with the positions of the 22 sample locations is presented in subsection 3.2.

- See the manuscript P. 10, Fig.1.

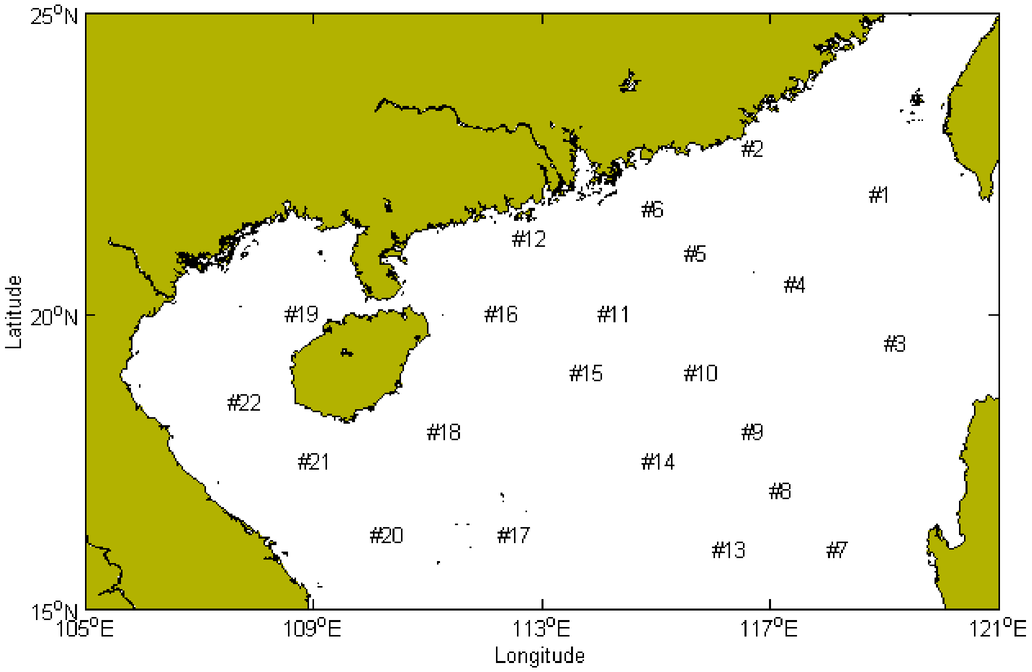

Fig. 1. The study sites in the study region.

(17) - page 10, line 10 and elsewhere, for me this is the sample. The values beyond the threshold are the peaks over threshold

Response: As suggested, "initial sample" was renamed "sample", and "sample" was renamed "extreme sample" (i.e., peaks over threshold).

(18) - page 11, line 4, I would add here that the extrapolation here is done fitting the peaks over threshold with a GPD.

Response: As suggested, the content in the corresponding line was rewritten.

(19) - page 11, line 5, you extrapolate only for high return periods, correct?

Response: Yes, high return periods are extrapolated. The corresponding content is emphasized in the manuscript.

(20) - page 11, lines 15-20. What technique did you use? ATSME, then the method should be better summarized somewhere, e.g. in section 2.

Response: As suggested, the ATSME was summarized in subsection 2.2.

- See the manuscript P. 7, subsection 2.2.

(21) - page 11, line 19: using ATSME the threshold range depends on the return period? This should be also explained in section 2, and how you can choose a single threshold (I guess, you can take the lowest of the upper limits of the ranges?).

Response: The stable threshold range shows a pattern associated with the return period. As suggested, this phenomenon was explained in subsection 2.2. In the ATSME, the suitable threshold is defined as the maximal threshold of the stable threshold range to guarantee design security.

- See the manuscript P. 8, lines 10-11: “Suitable threshold. Determine the suitable threshold within the stable threshold range, such as the maximal threshold.”
- See the manuscript P. 8, lines 12-18; P. 9, lines 1-2: “By the ATSME, a unique threshold is determined within a uniquely stable threshold range for a specific return period. Liang et al. (2019) found that the stable threshold range shows a pattern associated with the return period. The minimal threshold of the stable threshold range controls the representativeness of the extreme sample; thus, the samples over the minimal threshold can represent extreme waves well, and the minimal thresholds for

different return periods remain constant. The maximal threshold of the stable threshold range controls the number of extreme samples, and a longer return period requires more extreme samples; thus, the maximal thresholds gradually decrease when the return period increases. Consequently, excluding the sample within the stable threshold ranges does not obviously influence the return significant wave heights, and a suitable threshold should be determined within the stable threshold range."

(22) page 12, line 7, peak -> maximum

Response: As suggested, "peak significant wave height" was renamed "maximal significant wave height".

(23) - section 5. This (lengthy) discussion does not entirely explain the (interesting) bimodal shape showed by the sample. Is it possible that the 2 modes correspond to 2 different physical characteristics of the TC in this area? Do you have this shape everywhere, or only in a few locations?

Response: As suggested, we have rephrased the content in Section 5 to present our ideas more concisely. The initial database and characteristics of tropical cyclones determine a bimodal shape. During a tropical cyclone, when the track is close and the intensity is strong, the maximal significant wave height can represent the extreme wave at the targeted location. However, it is difficult to determine the extreme sample through track threshold and intensity threshold. In this study, we use a fixed distance to identify the initial database at the study site. When the distance between the centre of the tropical cyclone and the study site is within 300 km, hourly significant wave heights simulated during this tropical cyclone are adopted as the initial database at the study site. This fixed distance allows some small samples (the corresponding track is far, or the intensity is weak) to be extracted.

Thus, other analyses are needed to identify the extreme sample from the sample, such as the sample distribution with the sensitivity of the return significant wave height.

At the 22 study sites in the SCS, a bimodal shape exists. We think that this bimodal shape is obvious in the tropical cyclone-dominated area when a fixed distance is used. In this area, the tropical cyclone always drives the storm wave, and the number of tropical cyclones is sufficiently large (the annual mean number is greater than 5 (Mazas and Hamm, 2011)).

- See the manuscript P. 19, lines 11-14: "Based on further analysis of this distribution, the initial database and characteristics of the tropical cyclones determine a bimodal shape. A fixed distance is used to identify the initial database at the study site. This fixed distance allows some small samples (the corresponding track is far, or the intensity is weak) to be extracted. Thus, other analyses are needed to identify the extreme sample from the sample."
- See the manuscript P. 19, lines 15-19: "Consequently, the results of this study present a concept linking the assessment of extreme significant wave heights with the characteristics of tropical cyclones in a tropical cyclone-dominated area. The sample at the targeted location is affected by the track and intensity of the tropical cyclone. Future studies are suggested to promote the assessment of extreme significant wave heights in a tropical cyclone. For example, the threshold may be determined directly through a combination of track threshold and intensity threshold."

(24) - page 16, line 1, remove waves

Response: As suggested, "waves" was removed.

(25) - page 16, line 11 "at location 1 above the threshold"

Response: As suggested, the content in the corresponding line was rewritten.

(26) - page 16, lines 12-17, remove the list of values, as they are already in table 2

Response: As suggested, the list of values was removed.

(27) - page 17, the meaning of figure 6 is not entirely clear. What do the author mean with the word "empirical"?

Response: As suggested, the meaning of Fig. 6 was clearly described in the manuscript. The quantile plot was discussed by Coles (2001) and produced by a free package running in R. The term "empirical" represents "empirical quantile", and "model" represents "model quantile".

- See the manuscript P. 15, lines 14-16: "The asymptotic tail approximation can be estimated by the quantile plot, which is discussed by Coles (2001) and produced by a free package running in R."

(28) - section 5: in the end it is not entirely clear how the authors selected the threshold. They used ATSME to select a range for each r.p., and then how did they choose a single threshold? Is it simply the separation point between the modes of the distribution? But that would not be general, as not all the distribution of TC extremes are bimodal.

Response: As suggested, the method of threshold selection was clearly described in Section 5. In the ATSME, the maximal threshold of the stable threshold range is used to extract the extreme sample.

In the tropical cyclone, the track and intensity affect the sample at the targeted location. To assess the extreme significant wave height, we use a fixed distance to identify the initial database at the study site. This fixed distance allows some small samples (the corresponding track is far, or the intensity is weak) to be extracted. Thus, other analyses are needed to identify the extreme sample from the sample. In the sample distribution, a separation distinguishes the high sample from the low sample. In addition, this separation is within the stable threshold range. Thus, this separation can be used to extract the extreme sample.

We think that this method is suitable in the tropical cyclone-dominated area when a fixed distance is used. In this area, the tropical cyclone always drives the storm wave, and the number of tropical cyclones is sufficiently large (the annual mean number is greater than 5 (Mazas and Hamm, 2011)). To guarantee design security, a sensitivity analysis is suggested to supplement the threshold selection in the distribution.

(29) - section 5: maybe a map with the 22 locations reporting, for example, the 100-year return level would be useful and informative.

Response: As suggested, a map with the 22 sample locations is shown in Fig. 1. In addition, the 100-year return level is presented in Tables 1 and 2.

(30) - the conclusion could be a little shorter and less technical.

Response: As suggested, we have rephrased the conclusion to present our ideas more concisely and strictly.

- See the manuscript P. 18, conclusions and discussions.

(31) - especially in the conclusion there are several error on English, that should be corrected (the conclusion is a key part of the manuscript).

Response: As suggested, we have carefully reviewed the conclusion. To further improve it, proofreading and language editing have been completed by American Journal Experts.

(32) - line 15: is this 2-modal distribution a consequence of the sampling technique, or is it general, with a physical explanation?

Response: The initial database and characteristics of tropical cyclones determine the bimodal shape. A fixed distance is used to identify the initial database at the study site.

This fixed distance allows some small samples (the corresponding track is far, or the intensity is weak) to be extracted. Thus, other analyses are needed to identify the extreme sample from the sample, such as the sample distribution with the sensitivity of the return significant wave height.

Referee #2

The manuscript "Study of the threshold for the POT method. . ." describes the evaluation of statistical methods to ascertain extreme value wave heights relating to tropical cyclone waves in the South China Sea. The paper is focused on the Peaks Over Threshold method, and accurately defining the cut-off (lower bound) for the extreme value wave heights. The paper is generally well written and well researched in terms of contextualizing the study in relation to existing relevant work.

However, as a general comment I would say this is a very dense paper, which focuses on a particularly specific topic. The paper has some repetition and would benefit from being thinned out considerably so the core relevance, results and impacts of the work are made clearer. Some paragraphs are very long and could be split down by a factor of two or three. To this end, the paper would benefit from at least one figure up front to break up the text and provide some background on the geographic area.

Response: Thank you for your evaluation of our research. As suggested, some contents in the manuscript have been rewritten to show our ideas more concisely. Some repetitive information was deleted to clearly show the core relevance, results and impacts of our work.

In the manuscript, the long paragraph was rephrased and divided into two or three paragraphs. In addition, figures and tables appear in appropriate locations to break up the text.

In Fig. 1, the study region with the 22 study sites is shown. The SCS is the largest and deepest marginal sea in the western Pacific Ocean. In this area, the tropical cyclone always drives the storm wave, and the number of tropical cyclones is sufficiently large. Thus, the extreme significant wave height can be assessed in a tropical cyclone.

To further improve the quality, proofreading and language editing have been completed by American Journal Experts.


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(1) The overall concept may be of general interest to readers of NHESS but the level of detail is not, and in some places it reads too much like a report than a research paper. The "so what" of the research needs to be better addressed in terms of applications to other work.

Response: As suggested, we have rephrased the manuscript to make it stricter and to present some of the contents in greater detail. We try to show our research more clearly to enable its application to other works.

(2) I feel the analysis is over-complicated somewhat. Have the authors given any thought to the notion that defining the lower bound wave height for the POT analysis may be as simple as locating where the wave height distribution deviates from a Rayleigh-type to some form of Generalized Extreme Value Distribution? If this is not the case, why not?

Response: As suggested, we have rephrased the paper to present our ideas more concisely.

In the SCS, Shao et al. (2018a) compared the AM method with the POT method. Due to a fixed time window (i.e., one year), the independence and number of samples cannot be guaranteed. In a tropical cyclone, the influence of this fixed time window is further exacerbated, even if the return period is close to the size of the database. Compared with the AM method, the POT method is a natural sampling method without additional limitations. When the threshold is suitable, the POT method can guarantee the representativeness and number of extreme samples. However, the process of threshold selection is relatively complex.

Shao et al. (2018a) and Liang et al. (2019) analysed the sensitivity of the return significant wave height to the threshold. The researchers found that a suitable threshold should be determined within the stable threshold range. However, a unique threshold cannot be directly selected. To determine a unique threshold, Shao et al. (2018a) defined the largest threshold within the common stable threshold range as the suitable threshold, and Liang et al. (2019) proposed the use of an ATSME. The ATSME selects the largest threshold within the stable threshold range as the suitable threshold for different return periods.

In this paper, we further studied the sensitivity with the characteristic of tropical cyclones. We want to present a concept linking the assessment with this characteristic in a tropical cyclone-dominated area. We analysed the track and intensity influences of tropical cyclones on the extreme wave at the targeted location and studied the distribution of the sample with the sensitivity. To validate the high sample in the distribution for extrapolation, we estimated the asymptotic tail approximation and estimation uncertainty. As mentioned, it is interesting to study the location of the distribution deviating from a Rayleigh-type to some GEV forms. Thank you for your suggestion. This concept is significant, and we may research this topic in our future studies.

- See the manuscript P. 3, lines 19-22; P. 4, lines 1-10: "Shao et al. (2018a) compared the annual maxima (AM) method (Tawn, 1988) with the POT method. The AM method is an easy sampling method that does not require additional work, as the method directly extracts the annual maximal significant wave height for extrapolation. However, the AM method has limitations in a fixed time window (i.e., one year), which cannot guarantee the independence and number of samples. The annual maximal significant wave height obtained from neighbouring years may originate from the same extreme wave; some maximal significant wave heights may be neglected (i.e., the annual maximal significant wave height may be smaller than some unselected maximal significant wave heights in other years), resulting in an insufficient number of samples, especially for a relatively long return period. In a tropical cyclone, the AM method's limitation is further exacerbated, even if the return period is close to the database size. The annual frequency, intensity and track of recorded tropical cyclones greatly vary, and corresponding waves have obvious differences. Shao et al. (2018a) found that the minimal sample may be much less than the maximal sample, and the minimal sample may be too small to represent the extreme wave (i.e., the minimal sample in the AM method is obviously smaller than the extreme sample in the POT method)."

- See the manuscript P. 4, lines 10-21: "Compared with the AM method, the POT method is a natural sampling method without additional limitations. When the threshold is suitable, the POT method can guarantee the representativeness and number of extreme samples. However, the threshold selection process is relatively complex. Shao et al. (2018a) and Liang et al. (2019) analysed the sensitivity of the return significant wave height to the threshold. The researchers found that the suitable threshold should be determined within the stable threshold range (i.e., a threshold range corresponding to a range of stable return significant wave heights). Based on this conclusion, Shao et al. (2018a) defined the largest threshold within the common stable threshold range as the suitable threshold, and Liang et al. (2019) proposed an Automated Threshold Selection Method based on the characteristic of Extrapolated significant wave heights (the acronym is ATSME). The ATSME employs the differences in extrapolated significant wave heights for neighbouring thresholds as the diagnostic parameters to identify the uniquely stable threshold range via an automated method and selects the largest threshold within the stable threshold range as the suitable threshold for different return periods."

(3) Can the authors provide a better definition for "when the tropical cyclone is close to the coast" and "when the intensity is high". Were there distance and intensity thresholds used for this analysis?

Response: As suggested, we explained the corresponding content regarding the track and intensity in the manuscript.

The track and intensity of tropical cyclones affect the sample at the targeted location. When the track of the tropical cyclone is close to the study site and the intensity of the tropical cyclone is strong, the corresponding wave is sufficiently strong to represent the extreme wave at the study site. In contrast, when the track is far or the intensity is weak, the corresponding wave is insufficiently strong. However, it is difficult to determine the extreme sample through the track threshold and intensity threshold. A combination of track and intensity is relatively complex. In this study, we use a fixed distance to identify the initial database at the study site. When the distance between the centre of the tropical cyclone and the study site is within 300 km, hourly significant wave heights simulated during this tropical cyclone are adopted as the initial database at the study site. This fixed distance allows some small samples (the corresponding track is far, or the intensity is weak) to be extracted. Thus, other analyses are needed to identify the extreme sample from the sample, such as the sample distribution with the sensitivity of the return significant wave height. We will continue to study the assessment in the tropical cyclone. We hope that we will discover a combination of track threshold and intensity threshold, or the results of this paper can stimulate more scholars to pay attention to this topic.

- See the manuscript P. 19, lines 15-19: “Consequently, the results of this study present a concept linking the assessment of extreme significant wave heights with the characteristics of tropical cyclones in a tropical cyclone-dominated area. The sample at the targeted location is affected by the track and intensity of the tropical cyclone. Future studies are suggested to promote the assessment of extreme significant wave heights in a tropical cyclone. For example, the threshold may be determined directly through a combination of track threshold and intensity threshold.”

Referee #3

The authors perform wave climate of South China Sea making usage of 40 years of wave hindcast data. The analysis is accomplished by a discussion on the statistical performance exhibited by a POT model at varying threshold.

The issue addressed by the authors is interesting, current and in line with the topics of the journal. However, here are some methodological aspects that deserve to be better presented and discussed.

Response: Thank you for your evaluation of our topic and research. As suggested, we have rephrased some contents in the manuscript to show the methodological aspects more clearly and strictly.

(1) Did the authors apply a temporal lag for declustering?

Response: In this study, a 40-year hindcast of tropical cyclone waves is employed as the initial database. The wind used to drive the wave is the blended wind, which covers the entire tropical cyclone process (not only the strong intensity process). The maximal significant wave height of the tropical cyclone wave is obtained during the simulation period. Thus, the maximal significant wave height can be directly extracted as the sample.

(2) It is not clear how they generalize the influence of trajectories by means of local conditions (which are not only function of the variable, but also of bathymetry/topography, diffraction and shoaling effects, ...). Please clarify.

Response: In this manuscript, we study the extreme significant wave height in the tropical cyclone. When the tropical cyclone track is close to the study site and the tropical cyclone intensity is strong, the wind near the study site is very strong, which primarily determines an extreme wave at the study site. Thus, the track and intensity can be used to analyse the extreme wave at the study site. Location conditions (such as bathymetry/topography, diffraction and shoaling effects) are too complex to be introduced in an extreme value analysis; however, these conditions have been reflected in the tropical cyclone wave simulation.

(3) How do they mean with "stable threshold"?

Response: As suggested, "stable threshold" was explained in the manuscript. In the sensitivity of the return significant wave height, when the return significant wave height is stable against an increasing threshold, the corresponding range of candidate thresholds is known as the stable threshold range.

- See the manuscript P. 4, lines 13-15: "The researchers found that the suitable threshold should be determined within the stable threshold range (i.e., a threshold range corresponding to a range of stable return significant wave heights)."

(4) Since every change on bin range of histogram implies changes on related minimum point, how do you set this parameter?

Response: As mentioned, the bin range plays a significant role in the sample distribution. In this study, this range is equal to the threshold interval ($\Delta u = \frac{um-u1}{Ntot}$) defined by Liang et al. (2019). u_1 is set as the minimal sample, u_m is set as the maximal sample, and N_{tot} is set as the number of samples. On the one hand, the sample distribution can be discussed with the sensitivity of the return significant wave height. On the other hand, this definition of the bin range (i.e., the mean interval of the sample) can reflect the sample characteristics in the distribution.

- See the manuscript P. 8, lines 1-3: "Candidate threshold. Identify the suitable range for the equally spaced and increasing candidate thresholds, (u_1, u_m), and the threshold interval, $\Delta u = \frac{um-u1}{Ntot}$. u_1 is set as the minimal sample, u_m is set as the maximal sample, and N_{tot} is set as the number of samples."

- See the manuscript P. 15, lines 1-2: “The sample is counted from 0 m to 15 m with an interval of 0.05 m, which is the same as the threshold interval.”

(5) Finally, the English language is unsuitable and a deep review with a native speaker is strongly recommended.

Response: As suggested, we have carefully reviewed the manuscript. To further improve the quality, proofreading and language editing have been completed by American Journal Experts.

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Extreme significant wave height of tropical cyclone waves in the South China Sea

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ABSTRACT

Extreme significant wave heights are assessed in the South China Sea (SCS), as assessments of wave heights are crucial for coastal and offshore engineering. Two significant factors include the initial database and assessment method. The initial database is a basis for assessment, and the assessment method is used to extrapolate appropriate return significant wave heights during a given period. In this study, a 40-year (1975-2014) hindcast of tropical cyclone waves is used to analyse the extreme significant wave height, employing the peak over threshold (POT) method with the generalized Pareto distribution (GPD) model. The peak excesses over a sufficiently large value (i.e., threshold) are fitted; thus, the return significant wave heights are highly dependent on the threshold. To determine a suitable threshold, the sensitivity of return significant wave heights and the characteristics of tropical cyclone waves are studied. The sample distribution presents a separation that distinguishes the high sample from the low sample, and this separation is within the stable threshold range. In addition, the asymptotic tail approximation and estimation uncertainty are reasonable based on the high sample value.

1. Introduction

Reasonable assessments of extreme significant wave heights are highly important for the security and expense of coastal defence and offshore structures (Ojeda and Guillén, 2006, 2008; Ojeda et al., 2010, 2011; Mortlock and Goodwin, 2015, 2016; Mortlock et al., 2017). To obtain this assessment, a sample is extracted from an accurate initial database, the extreme sample is identified by a reliable sampling method, and then, an appropriate probability distribution model is fitted.

The initial database highly influences the assessment of extreme significant wave heights (Godoi et al., 2017; Lucas et al., 2017; Li et al., 2018). In previous studies, the long-term continuous database is usually employed as the initial database, such as a 32-year measured significant wave height in the Gulf of Maine (Viselli et al., 2015), a 44-year hindcasted significant wave height in the North Atlantic Ocean (Muraleedharan et al., 2016) and a 22-year hindcasted significant wave height in the Yellow Sea (Gao et al., 2018). Considering that the extreme significant wave height should be extrapolated based on an independent and identically distributed database required for the extreme value theory (EVT) (Coles, 2001; Sobradelo et al., 2011), these time series buoy measurements and numerical hindcasts should be processed. The homogenous methodology is used to extract homogenous significant wave heights via separation in carefully chosen directional sectors and seasonal analyses as well as separation of the sea state into independent wave systems (Lerma et al., 2015; Solari and Alonso, 2017). Declustering methodology, such as the double-threshold approach (Mazas and Hamm, 2011) and minimum separation time method (Kapelonis et al., 2015), is used to differentiate the individual wave event. However, these methodologies may introduce uncertainty in the sample (such as the subjectivity of practitioners in the selections of initial threshold and time window), which influences the extreme sample selection.

The peak over threshold (POT) method (Goda et al., 2001) is widely used to identify the peak excesses over a threshold (Ferreira and Guedes Soares, 1998; Soares and Scotto, 2004; Caires and Sterl, 2005; Benetazzo et al., 2012; You and Callaghan, 2013; Xiao et al., 2017). Additionally, the generalized Pareto distribution (GPD) model (Coles, 2001) is widely used to extrapolate extreme significant wave heights (Martucci et al., 2010; Blanchet et al., 2015; Kapelonis et al., 2015; Boessenkool et al., 2017; Muhammed Naseef and Sanil Kumar, 2017). This method (i.e., the POT/GPD method) makes the most of the samples and extends the return period when the threshold is suitable (Alves and Young, 2003; You, 2011; Vanem, 2015a; Samayam et al., 2017; Shao et al., 2017). To select a suitable threshold, many methods have been proposed, such as graphical diagnostics (Coles, 2001; Sánchez-Arcilla et al., 2008; Bernardara et al., 2014), empirical methods (Ferreira et al., 2003; Neves and Alves, 2004; Reiss and Thomas, 2007), probabilistic-based techniques (Hill, 1975; Beirlant et al., 2006; Goegebeur et al., 2008), computational approaches (Danielsson et al., 2001; Beguería, 2005; Solari et al., 2017) and mixture models (Carreau and Bengio, 2009; Eastoe and Tawn, 2010; MacDonald et al., 2011). Among these methods, a graphical diagnostic referred to as the sensitivity of the return significant wave height to the threshold (Scarrott and MacDonald, 2012) is commonly accepted (Petrov et al., 2013; Northrop and Coleman, 2014; Vanem, 2015b; Northrop et al., 2017; Sulis et al., 2017).

In the South China Sea (SCS), time series wave parameters have been simulated (Zheng et al., 2012; Mirzaei et al., 2015; Yaakob et al., 2016), and extreme waves have been investigated based on long-term continuous data (Zheng et al., 2015; Chen et al., 2017; Wang et al., 2018). In addition, Shao et al. (2018a) and Liang et al. (2019) analysed the extreme significant wave height in a tropical cyclone. Shao et al. (2018a) compared the annual maxima (AM) method (Tawn, 1988) with the POT method. The AM method is an easy sampling method that does not require additional work, as the method directly extracts the annual maximal significant wave height for extrapolation. However, the AM method has limitations in a fixed time window (i.e., one year), which cannot guarantee the independence and number of samples. The annual maximal significant wave height obtained from neighbouring years may originate from the same extreme wave; some maximal significant wave heights may be neglected (i.e., the annual maximal significant wave height may be smaller than some unselected maximal significant wave heights in other years), resulting in an insufficient number of samples, especially for a relatively long return period. In a tropical cyclone, the AM method's limitation is further exacerbated, even if the return period is close to the database size. The annual frequency, intensity and track of recorded tropical cyclones greatly vary, and corresponding waves have obvious differences. Shao et al. (2018a) found that the minimal sample may be much less than the maximal sample, and the minimal sample may be too small to represent the extreme wave (i.e., the minimal sample in the AM method is obviously smaller than the extreme sample in the POT method). Compared with the AM method, the POT method is a natural sampling method without additional limitations. When the threshold is suitable, the POT method can guarantee the representativeness and number of extreme samples. However, the threshold selection process is relatively complex. Shao et al. (2018a) and Liang et al. (2019) analysed the sensitivity of the return significant wave height to the threshold. The researchers found that the suitable threshold should be determined within the stable threshold range (i.e., a threshold range corresponding to a range of stable return significant wave heights). Based on this conclusion, Shao et al. (2018a) defined the largest threshold within the common stable threshold range as the suitable threshold, and Liang et al. (2019) proposed an Automated Threshold Selection Method based on the characteristic of Extrapolated significant wave heights (the acronym is ATSME). The ATSME employs the differences in extrapolated significant wave heights for neighbouring thresholds as the diagnostic parameters to identify the uniquely stable threshold range via an automated method and selects the largest threshold within the stable threshold range as the suitable threshold for different return periods.

In this study, the assessment of extreme significant wave heights is further studied in the SCS. Before the assessment, the meteorological characteristics are analysed to identify extreme weather. In the SCS, the tropical cyclone always drives the storm wave (Anoop et al., 2015; Hithin et al., 2015; Sanil Kumar and Anoop, 2015; Ojeda et al., 2017; Wang et al., 2017; Mortlock et al., 2018; Sanil Kumar et al., 2018), and the number of tropical cyclones is sufficiently large. Thus, it is possible to study the extreme significant wave height in a tropical cyclone. To achieve the assessment, a 40-year (1975-2014) hindcasted significant wave height of tropical cyclone waves is employed as the initial database. Considering that the hindcast is independently simulated during the tropical cyclone recorded in the SCS, the maximal significant wave height of the tropical cyclone wave can be directly extracted as the sample when the tropical cyclone influences the wave at the targeted location. Based on the sample, the POT method threshold is studied. By analysing the sensitivity of the return significant wave heights and the characteristics of the tropical cyclone waves, the sample distribution presents a separation within the stable threshold range. As validated by the asymptotic tail approximation and estimation uncertainty, the high sample shown in the distribution of the sample is suitable for extrapolating extreme significant wave heights in the SCS.

The article is structured as follows. In the next section, the POT/GPD and ATSME are introduced. The initial data and study sites are presented in Section 3. In Section 4, the sampling method is described. In Section 5, the characteristics of tropical cyclone waves are discussed. Finally, the conclusions and discussions are presented in Section 6.

2. Background

2.1 POT/GPD

The POT method extracts the maximal significant wave heights above a selected value (i.e., threshold), u, as the extreme sample. For u, which is sufficiently large, the distribution function of peak excesses can be approximated by a member of the GPD (Pickands, 1975; Embrechts et al., 1997):

$$F_u\left(Hs^*\right)=\begin{cases}1-(1+k\dfrac{Hs^*}{\sigma})^{-\frac{1}{k}} & k\neq 0\\ 1-\exp\left(-\dfrac{Hs^*}{\sigma}\right) & k=0\end{cases} \tag{1}$$

where Hs^{*} represents the peak excess over the threshold; σ represents the scale parameter; and k represents the shape parameter. These GPD parameters (σ and k) are estimated using the maximum likelihood estimation method, which is recommended by Mazas and Hamm (2011):

$$\ln L(k,\sigma;Hs)=\begin{cases}-N\ln\sigma+(\frac{1}{k}-1)\sum_{j=1}^{N}\ln(1-\frac{kHs_j}{\sigma}) & k\neq 0\\ -N\ln\sigma-\frac{1}{\sigma}\sum_{j=1}^{N}Hs_j, & k=0\end{cases} \tag{2}$$

where N represents the number of events exceeding the threshold (i.e., the number of extreme samples), and Hs represents the maximal significant wave height.

The return significant wave height for the i-year, Hs_i, is defined as follows:

$$Hs_i=F_u^{-1}(1-\frac{1}{i}) \tag{3}$$

Thus, the value can be calculated with the following equation:

$$Hs_i=\begin{cases}u+[(\frac{N}{N_T}i)^k-1]\sigma/k & k\neq 0\\ u+\sigma\ln(\frac{N}{N_T}i) & k=0\end{cases} \tag{4}$$

where N_T represents the size of the dataset.

2.2 ATSME

The terms u_1 ,…, u_m are equally spaced with increasing candidate thresholds. $Hs_{i,j}$ represents the return significant wave height for the i-year based on the threshold of u_j. The difference, $\Delta Hs_{i,j}$, in i-year return significant wave heights ($Hs_{i,j}$ and $Hs_{i,j-1}$) for neighbouring thresholds (u_j and u_{j-1}) is defined as follows:

$$\Delta Hs_{i,j} = Hs_{i,j} - Hs_{i,j-1} \tag{5}$$

To study the influence of the excluded samples on the return significant wave height with an increasing threshold and to select a suitable threshold, the ATSME is defined as follows (Liang et al., 2019):

(1) Sample. Take the sample from the initial database under an independent and identically distributed assumption.

(2) Candidate threshold. Identify the suitable range for the equally spaced and increasing candidate thresholds, (u_1 , u_m), and the threshold interval, $\Delta u = \frac{u_m - u_1}{N_{tot}}$. u_1 is set as the minimal sample, u_m is set as the maximal sample, and N_{tot} is set as the number of samples.

(3) Return period and value. Choose the order of i ($i = i_1, \ldots, i_{n_i}$) for different return periods, which is dependent on N_T and the requirement of practitioners. Extrapolate the return significant wave height for the i -year, $Hs_{i,j}$, which corresponds to every candidate threshold, u_j .

(4) Stable threshold range. Calculate the difference, $\Delta Hs_{i,j}$, in the return significant wave height for neighbouring thresholds. Define a characteristic parameter, $ch_{i,j}$, to record the stable characteristics of the return significant wave heights. Find the uniquely stable threshold range for the i -year return period.

(5) Suitable threshold. Determine the suitable threshold within the stable threshold range, such as the maximal threshold.

By the ATSME, a unique threshold is determined within a uniquely stable threshold range for a specific return period. Liang et al. (2019) found that the stable threshold range shows a pattern associated with the return period. The minimal threshold of the stable threshold range controls the representativeness of the extreme sample; thus, the samples over the minimal threshold can represent extreme waves well, and the minimal thresholds for different return periods remain constant. The maximal threshold of the stable threshold range controls the number of extreme samples, and a longer return period requires more extreme samples; thus, the maximal thresholds gradually decrease when the return period increases. Consequently, excluding the sample within the stable threshold ranges does not obviously influence the return significant wave heights, and a suitable threshold should be determined within the stable threshold range.

3. Initial data and study sites

3.1 Initial data

Significant wave heights from a 40-year hindcast of tropical cyclone waves (Shao et al., 2018a) are adopted as the initial database, which is simulated using the third-generation spectral wind-wave model SWAN (an acronym for Simulating WAves Nearshore) (Booij et al., 1999; Mortlock et al., 2014; Amrutha et al., 2016). This model is forced by the blended wind, which is obtained by combining the European Centre for Medium-Range Weather Forecasts reanalysis wind and Holland model wind (Shao et al., 2018b). The spatial resolution is 0.0625 ° for both longitude and latitude, and the temporal resolution is 1 h. From 1975 to 2014, waves are simulated only during 974 independent tropical cyclones.

3.2 Study sites

To analyse the extreme significant wave height, 22 locations were selected as the study sites (Fig. 1). When the distance between the centre of the tropical cyclone and the study site is within 300 km, hourly significant wave heights simulated during this tropical cyclone are adopted as the initial database at the study site. At the 22 study sites, the number of recorded tropical cyclones is 247 to 403, and the annual mean number of recorded tropical cyclones is 6.175 to 10.075. The corresponding tropical cyclone waves are sufficient for assessing extreme significant wave heights in the SCS (Mazas and Hamm, 2011).

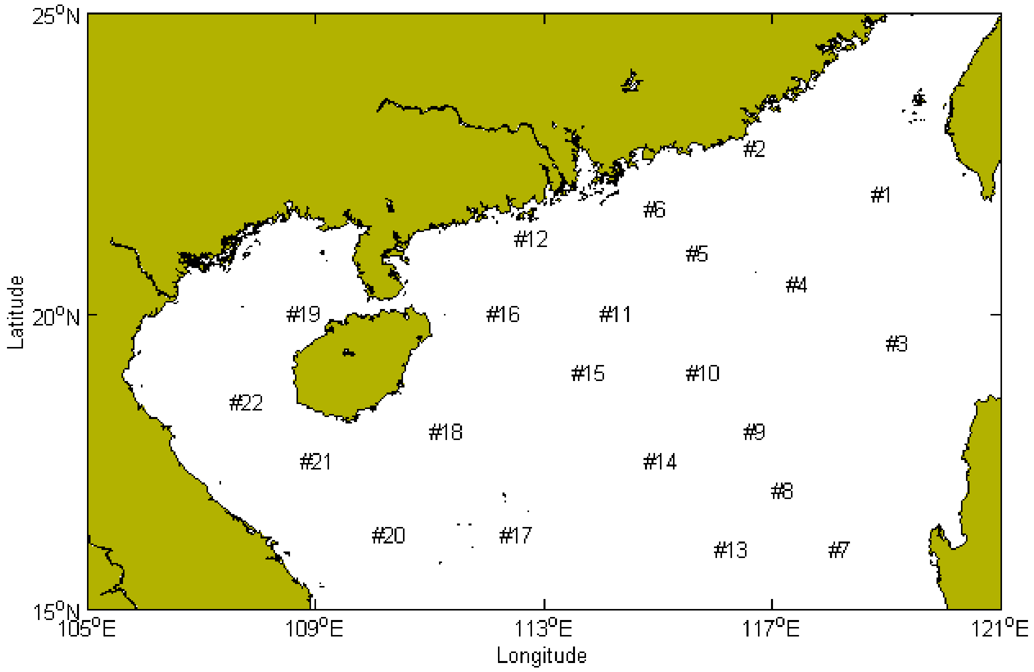

Fig. 1. The study sites in the study region.

4. Study of the POT method

4.1 Sample

As required by the EVT, the extreme significant wave height should be extrapolated based on the independent wave under the same type of meteorological event (Lerma et al., 2015; Solari and Alonso, 2017). Considering that the initial database is simulated only during the independent tropical cyclone, the maximal significant wave height of recorded tropical cyclone waves can be directly extracted as the sample at the study site. For example, 328 tropical cyclones are recorded at location #1; thus, 328 maximal significant wave heights during these tropical cyclones are extracted as the sample.

4.2 Sensitivity of return values to threshold

Sensitivity of the return significant wave height to the threshold can be used in threshold selection. This method fits the GPD over a range of candidate thresholds and selects the suitable threshold by identifying the stability of the return significant wave heights. If return significant wave heights are insensitive to the threshold, the corresponding threshold can be selected as the suitable threshold. The benefit of this method is that it requires practitioners to graphically inspect and comprehend the data features and assess the uncertainty of the candidate thresholds (Scarrott and MacDonald, 2012). The drawback of this method is that the threshold is not uniquely selected, and another criterion is needed to identify the optimal threshold (Lerma et al., 2015).

Shao et al. (2018a) and Liang et al. (2019) analysed the sensitivity of the return significant wave height and provided threshold selection criteria to determine a unique threshold. Liang et al. (2019) diagnosed the return significant wave height within the stable threshold range. If some return significant wave heights within the stable threshold range are relatively different from the others, the corresponding candidate thresholds are rejected. Thus, the conclusions of Liang et al. (2019) on the sensitivity of the return significant wave height are employed in this study. For example, at location #1, the equally spaced with increasing candidate thresholds are identified by a threshold interval of 0.05 m, and the stable threshold ranges for the 50-year, 100-year, 150-year and 200-year return periods are (3.3 m, 5.75 m), (3.3 m, 5.25 m), (3.3 m, 4.6 m) and (3.3 m, 4.5 m), respectively.

5. Characteristics of tropical cyclone waves

To further analyse the candidate thresholds within the stable threshold range, the characteristics of tropical cyclone waves are investigated. The track and intensity of tropical cyclones affect the waves at the study site. When the tropical cyclone track is close to the study site and the intensity of the tropical cyclone is strong, the corresponding wave is sufficiently strong for representing the extreme wave at the study site. In this case, the maximal significant wave height of this tropical cyclone wave should be extracted as the extreme sample. For example, at location #1, the maximal significant wave heights during tropical cyclones Pabuk in 2007, Linfa in 2009, Molave in 2009 and Meranti in 2010 are 5.27 m, 8.17 m, 9.48 m and 4.51 m, respectively. The tracks of these tropical cyclones are close to location #1, and the intensities of these tropical cyclones are strong when they influence the waves at location #1 (shown in Fig. 2).

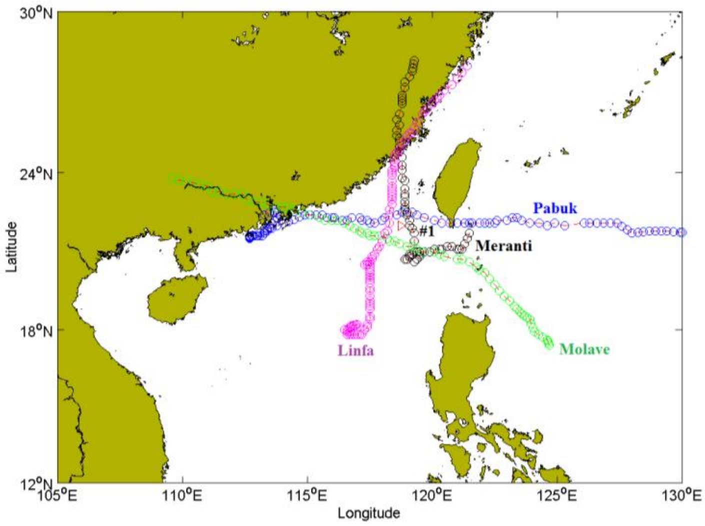

Fig. 2. Tracks of the centres of tropical cyclones Pabuk, Linfa, Molave and Meranti (triangle represents location #1, curves represent tracks of centres and circles represent locations of centres).

In contrast, when the track of the tropical cyclone is far from the study site or the intensity of the tropical cyclone is weak, the corresponding wave is insufficiently strong to represent the extreme wave at the study site. In this case, the maximal significant wave height of this tropical cyclone wave should not be extracted as the extreme sample. For example, at location #1, the maximal significant wave heights during tropical cyclones Maria in 2000 and Toraji in 2001 are 2.59 m and 1.57 m, respectively. Although the intensities of these tropical cyclones are strong when they influence the waves at location #1, the tracks of these tropical cyclones are too far from location #1 (shown in Fig. 3). The maximal significant wave heights during tropical cyclones Trami in 2001 and Wutip in 2007 are 2.47 m and 2.20 m, respectively. Although the tracks of these tropical cyclones are close to location #1, the intensities of these tropical cyclones are weak when these tropical cyclones influence the waves at location #1 (shown in Fig. 4). The maximal significant wave heights during tropical cyclones Kai-tak in 2005 and Kammuri in 2008 are 1.11 m and 2.36 m, respectively. The tracks of these tropical cyclones are far from location #1, and the intensities of these tropical cyclones are weak when they influence the waves at location #1 (shown in Fig. 5).

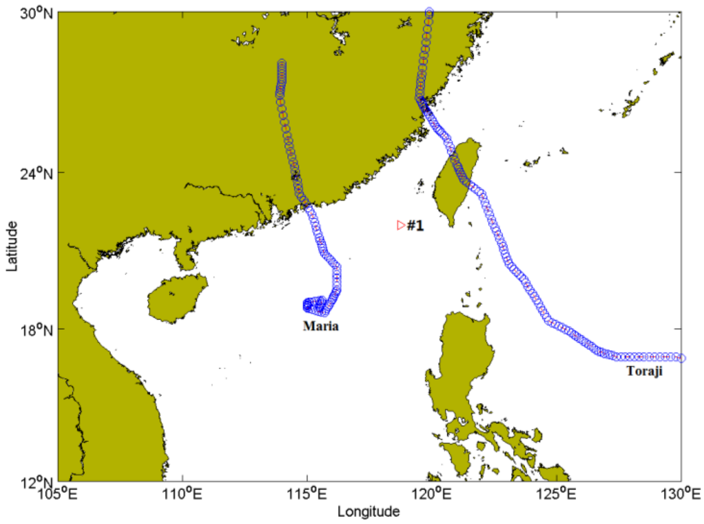

Fig. 3. Tracks of the centres of tropical cyclones Maria and Toraji (triangle represents location #1, curves represent tracks of centres and circles represent locations of centres).

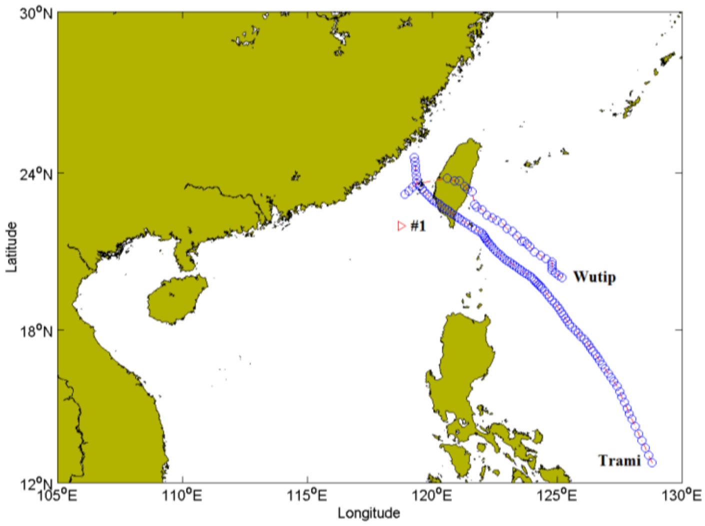

Fig. 4. Tracks of the centres of tropical cyclones Trami and Wutip (triangle represents location #1, curves represent tracks of centres and circles represent locations of centres).

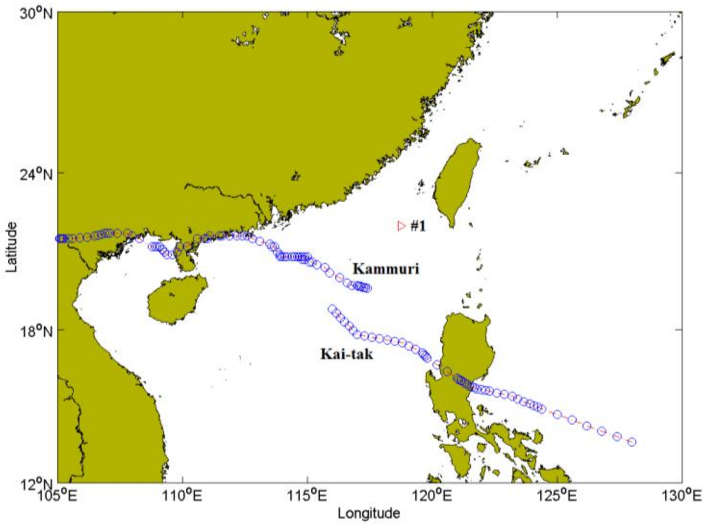

Fig. 5. Tracks of the centres of tropical cyclones Kai-tak and Kammuri (triangle represents location #1, curves represent tracks of centres and circles represent locations of centres).

The track and intensity influences of the tropical cyclones are reflected in the sample distribution (i.e., the distribution of the maximal significant wave height). In Fig. 6, the distribution of the sample at location #1 is presented. The sample is counted from 0 m to 15 m with an interval of 0.05 m, which is the same as the threshold interval. The samples are concentrated in two ranges: range 1 (0-4.15 m) and range 2 (4.15-15 m), with a separation value of 4.15 m (the curve is plotted to clearly show these ranges). In range 1, 191 samples from 191 independent tropical cyclone waves are found. The corresponding tropical cyclone has a weak influence on the wave at location #1, and its track and intensity are similar to those shown in Figs. 3, 4 and 5. In range 2, 137 samples from 137 independent tropical cyclone waves are found. The corresponding tropical cyclone has a strong influence on the wave at location #1, and its track and intensity are similar to those shown in Fig. 2. The sample distribution has a natural separation, distinguishing the high sample from the low sample. Linking the distribution with the sensitivity of the return significant wave height, this separation (the corresponding annual mean number of extreme samples is 3.425) is within the stable threshold range shown in subsection 4.2.

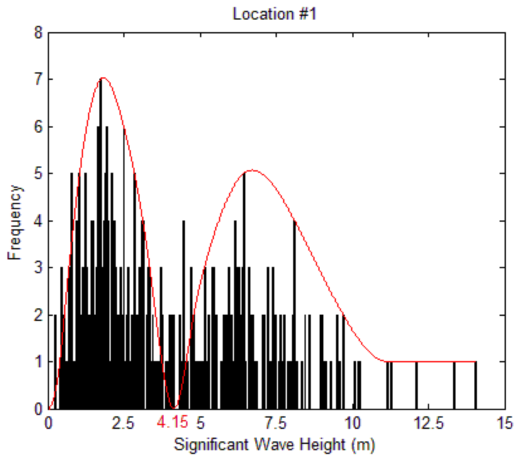

Fig. 6. Histogram of the maximal significant wave height from 0 m to 15 m with intervals of 0.05 m at location #1.

To further validate the separation, the asymptotic tail approximation and estimation uncertainty are analysed. The asymptotic tail approximation can be estimated by the quantile plot, which is discussed by Coles (2001) and produced by a free package running in R. In Fig. 7, the quantile plot for the threshold of 4.15 m is presented, which shows that there are generally few differences between the empirical and fitted quantiles, indicating a good fit for the selected threshold. In Table 1, the return significant wave height with the confidence interval is shown. The likelihood method (Schendel and Thongwichian, 2017) reparametrizes the likelihood in terms of the unknown quantile and uses profile likelihood arguments to construct an approximate 95% confidence interval. At location #1, the confidence intervals indicate that the variance in the extrapolated significant wave heights is acceptable.

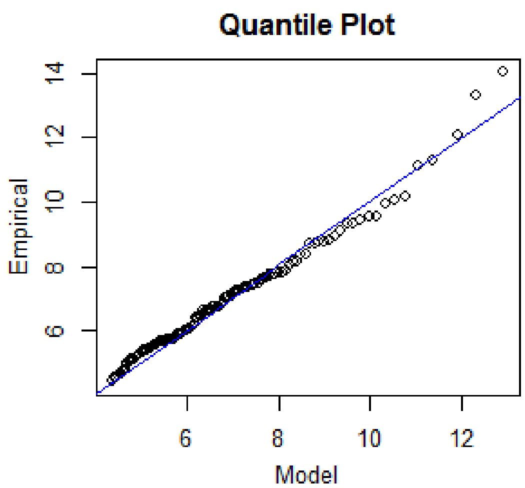

Fig. 7. The quantile plot for GPD-fitted maximal significant wave heights at location #1 for the threshold of 4.15 m.

Table 1
Statistics for the return significant wave heights and confidence intervals at location #1 for the threshold of 4.15 m.

Return Period	Return Significant Wave Height (m)	Confidence Interval (m)	Width of Confidence Interval (m)
50-year	12.07	(11.39, 13.08)	1.69
100-year	12.70	(12.02, 13.92)	1.90
150-year	13.00	(12.31, 14.36)	2.05
200-year	13.20	(12.50, 14.66)	2.16

The same conclusion can be reached at the other 21 study sites. For example, the sample distributions at locations #7 and #10 (Fig. 8) present separation values of 3.35 m and 4.1 m, respectively. Based on these separation values, the GPD model is used to extrapolate the return significant wave heights for return periods of 50-year, 100-year, 150-year and 200-year (Table 2). To validate the reliability of the return significant wave heights, the asymptotic tail approximation and estimation uncertainty are analysed. For example, the quantile plots at locations #7 and #10 are presented in Fig. 9, and the confidence intervals at 21 study sites are shown in Table 2. The fits of the results are good, and the uncertainties of the return significant wave heights are acceptable.

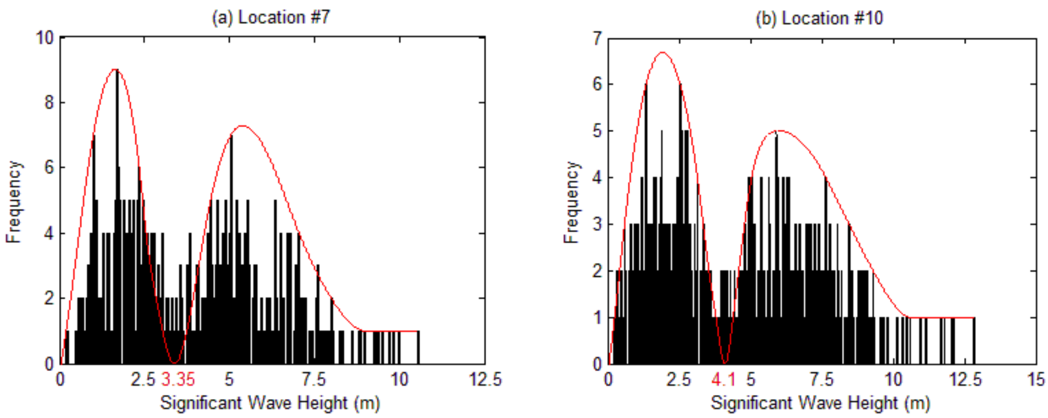

Fig. 8. Histograms of the maximal significant wave heights at locations #7 and #10.

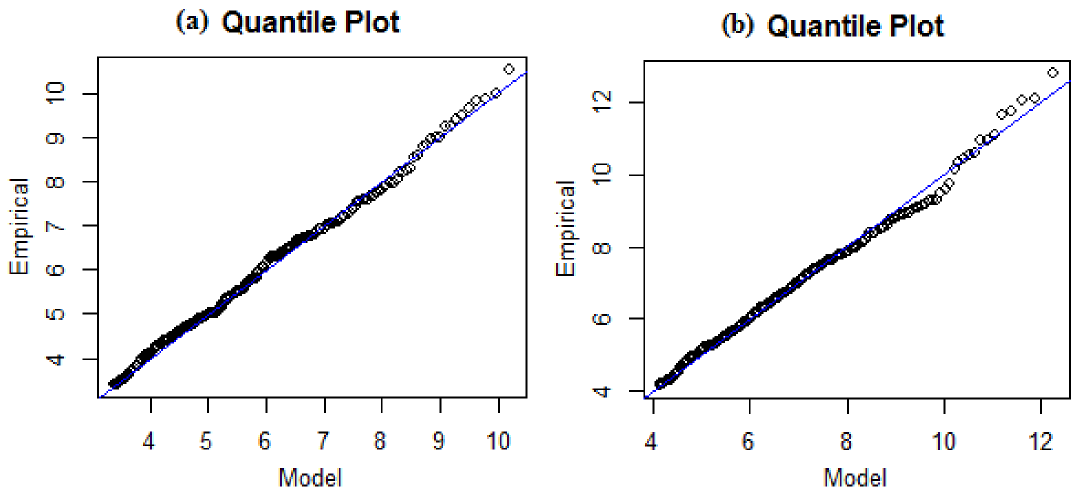

Fig. 9. Quantile plots for GPD-fitted maximal significant wave heights: (a) for the threshold of 3.35 m at location #7 and (b) for the threshold of 4.1 m at location #10.

Table 2
Statistics for thresholds, extreme samples and return significant wave heights with 95% confidence intervals.

Location	Threshold (m)	Annual Mean Number of Extreme Samples	Return Significant Wave Heights (m) with 95% Confidence Intervals			
			50-year	100-year	150-year	200-year
#2	3.05	3.475	9.25 (8.88, 9.88)	9.58 (9.19, 10.45)	9.74 (9.37, 10.74)	9.86 (9.46, 10.92)
#3	5	3.375	11.17 (10.74, 11.89)	11.45 (11.02, 12.34)	11.61 (11.18, 12.60)	11.71 (11.29, 12.78)
#4	4.85	4.175	12.00 (11.25, 12.91)	12.24 (11.65, 13.26)	12.52 (11.93, 13.66)	12.70 (12.09, 13.94)
#5	4.95	3.975	11.84 (11.17, 12.80)	12.53 (11.81, 13.74)	12.83 (12.13, 14.25)	13.06 (12.34, 14.61)
#6	4.5	3.625	10.16 (9.92, 10.64)	10.45 (10.19, 11.01)	10.56 (10.32, 11.19)	10.65 (10.39, 11.30)
#7	3.35	5.325	9.68 (9.39, 10.11)	9.96 (9.66, 10.50)	10.10 (9.82, 10.71)	10.19 (9.90, 10.84)
#8	3.6	5.55	10.36 (10.05, 10.84)	10.64 (10.26, 11.18)	10.72 (10.35, 11.32)	10.91 (10.51, 11.48)
#9	3.75	5.5	10.86 (10.49, 11.39)	11.14 (10.79, 11.82)	11.28 (10.93, 12.04)	11.34 (10.98, 12.14)
#10	4.1	5.3	11.40 (10.90, 12.04)	11.87 (11.41, 12.68)	12.11 (11.58, 13.03)	12.26 (11.78, 13.23)
#11	4.25	4.75	11.44 (11.11, 12.03)	11.88 (11.56, 12.59)	12.14 (11.78, 12.87)	12.29 (11.92, 13.05)
#12	3.7	3.675	9.69 (9.37, 10.24)	9.89 (9.56, 10.57)	9.93 (9.67, 10.67)	10.02 (9.76, 10.80)
#13	3.65	5.025	11.10 (10.48, 12.07)	11.63 (10.93, 12.88)	11.88 (11.15, 13.30)	12.11 (11.35, 13.68)
#14	4.15	4.8	11.06 (10.65, 11.70)	11.40 (10.99, 12.18)	11.54 (11.14, 12.41)	11.66 (11.26, 12.59)
#15	4.85	4.2	11.31 (10.92, 11.90)	11.74 (11.34, 12.44)	11.95 (11.54, 12.71)	12.07 (11.67, 12.89)
#16	4.45	3.825	10.91 (10.74, 11.38)	11.31 (11.14, 11.83)	11.46 (11.28, 12.02)	11.75 (11.56, 12.33)
#17	3.05	4.775	10.31 (9.65, 11.59)	10.88 (10.03, 12.65)	11.08 (10.18, 13.15)	11.26 (10.35, 13.57)
#18	3.65	4.25	11.63 (11.04, 12.65)	12.00 (11.38, 13.30)	12.18 (11.53, 13.66)	12.36 (11.70, 13.95)
#19	3.55	2.275	7.87 (7.65, 8.33)	8.16 (7.93, 8.70)	8.21 (8.00, 8.83)	8.28 (8.06, 8.91)
#20	3.65	3.575	10.07 (9.53, 11.02)	10.50 (9.94, 11.71)	10.64 (10.05, 12.02)	10.84 (10.23, 12.35)
#21	2.9	4	10.10 (9.32, 11.59)	10.70 (9.87, 12.83)	10.96 (9.94, 13.37)	11.12 (10.21, 13.99)
#22	3	2.9	9.10 (8.57, 10.29)	9.45 (8.87, 11.01)	9.58 (9.00, 11.37)	9.71 (9.09, 11.68)

6. Conclusions and discussions

In general, the threshold selection criterion of Shao et al. (2018a) can be used to assess the extreme significant wave height. However, some return significant wave heights within the stable threshold range may be relatively different from the others, especially for a short return period. For example, at location #12, the return significant wave heights for the return periods of 50-year, 100-year, 150-year and 200-year are 9.59 m, 9.86 m, 9.99 m and 10.06 m, respectively; however, under the criterion of Liang et al. (2019), the corresponding return significant wave heights are 9.69 m, 9.89 m, 9.96 m and 10.05 m, respectively. Benefitting from a diagnostic process of Liang et al. (2019), the return significant wave heights are more stable than those of Shao et al. (2018a). Comparing Table 9 of Shao et al. (2019) with Tables 1 and 2 in this study, the return significant wave heights for the return periods of 50-year, 100-year, 150-year and 200-year are very similar at the same 22 study locations. Both groups of return significant wave heights are reasonable in the SCS. However, the threshold selection criterion in this study is suitable only in a tropical cyclone-dominated area.

Based on a separation within the stable threshold range, a unique threshold can be identified without a subjective definition. Based on further analysis of this distribution, the initial database and characteristics of the tropical cyclones determine a bimodal shape. A fixed distance is used to identify the initial database at the study site. This fixed distance allows some small samples (the corresponding track is far, or the intensity is weak) to be extracted. Thus, other analyses are needed to identify the extreme sample from the sample.

Consequently, the results of this study present a concept linking the assessment of extreme significant wave heights with the characteristics of tropical cyclones in a tropical cyclone-dominated area. The sample at the targeted location is affected by the track and intensity of the tropical cyclone. Future studies are suggested to promote the assessment of extreme significant wave heights in a tropical cyclone. For example, the threshold may be determined directly through a combination of track threshold and intensity threshold.

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