

Article



Study of Directional Declustering for Estimating Extreme Wave Heights in the Yellow Sea

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Abstract: The study of extreme waves is important for the protection of coastal and ocean structures. In this work, a 22-year (1990–2011) wave hindcast in the Yellow Sea is employed to perform the assessment of extreme significant wave heights in this area. To extract the independent sample from this database, the fixed window method is used, which takes the peak significant wave height within five d. With the selected samples, directional declustering is studied to extract the homogenous sample. The results show that most of the independent samples (especially large samples) are observed in the North. In this direction, the peak over threshold (POT) method is used to extract the extreme sample from the homogenous sample, and then the generalized Pareto distribution model is used to extrapolate the extreme significant wave height. In addition to this combination, the annual maxima method with the Gumbel model is also used for estimating extreme values. The comparisons show that the return significant wave heights of the first combination are reliable, resulting from a flexible sampling window in the POT method. With this conclusion, the extreme significant wave height is extrapolated from the Yellow Sea, which can be used to protect the structure in the main directional bin.

Keywords: directional declustering; peak over threshold; generalized Pareto distribution; directional design wave height; Yellow Sea

1. Introduction

An appropriate estimation of extreme waves plays an important role in protecting the coastal and ocean structures [1]. This estimation affects the design wave height [2], which implies a balance between the security and expenditure of structures [3]. In the engineering community, a large design value is likely to increase the engineering expenditure, but a small design value is unlikely to ensure the engineering security [4]. Thus, the return significant wave height with its return period should be prudently determined.

To extrapolate the extreme significant wave height, the initial database needs to be selected first [5], which is derived from the instrumental measurement (consisting of, for example, the buoy measurement [6] and satellite measurement [7]) and numerical hindcast [8]. In fact, although the accuracy of instrumental measurements may be better than that of hindcasted data [9], the latter data are usually used due to their long duration, large coverage and regular temporal resolution [10]. Considering these merits, a 22-year time series hindcast in the Yellow Sea [11] is employed to estimate the extreme wave in this area. To perform this estimation, the independent and identically distributed sample should be extracted from the initial database [12], which is required by the extreme value theory [13]. In previous studies, many methods [14–16] have been proposed to satisfy the independence assumption. For example, Gao et al. [17] applied the fixed window method in the Yellow Sea after

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analysing the meteorological characteristics in this area. The peak significant wave heights within a time window of five d are extracted as the independent sample. In this study, the fixed window method is revisited in the Yellow Sea with the same time window. To validate the reliability of extracted independent samples, these samples are analysed in the time series initial database by the graphical diagnostic. The minimal significant wave height in the storm interval is compared with the significant wave heights at the initiation of the previous storm and the end of the following storm. When the minimal value is similar to the significant wave heights at the initiation or end, two consecutive storms are regarded as two individual wave events.

Independent samples of different physical processes have different parent distributions [18]. Thus, sample homogeneity is needed before extracting the extreme sample for extrapolation [19]. If this process is ignored, extreme samples derived from different meteorological phenomena may be used to fit one distribution model, although these samples are not identically distributed [20]. In the previous studies, many methods [21–23] have been proposed for extracting the homogenous sample. Among these methods, directional declustering is widely used in coastal and ocean engineering because this method can be employed to protect the structure in a special direction [24]. For example, Jonathan and Ewans [25] analysed the homogenous sample and studied the extreme wave in the main directional bin, through separating the independent sample into the directional bins. Lerma et al. [26] studied the extreme samples in the directional bins and analysed the distribution of extreme waves along the French coast. In this study, with the independent samples extracted by the fixed window method, directional declustering is analysed in the Yellow Sea. The independent samples are separated into eight directional bins by analysing the mean wave direction, and the results show that these samples (especially large samples) are mostly observed in the North.

The peak over threshold (POT) method [13] and annual maxima (AM) method [27] are common methods extracting the extreme sample from the homogenous sample, which select the peak significant wave height over the threshold and the annual maximal significant wave height as the extreme sample, respectively. By fitting these extreme samples, the generalized Pareto distribution (GPD) model [28] and Gumbel model [29], respectively, are widely employed to extrapolate the required return significant wave heights through constructing long-term distributions [30]. In this study, the POT/GPD method and AM/Gumbel method are used to estimate the extreme wave in the Yellow Sea, based on the homogenous sample in the North that is extracted by directional declustering. The comparison results show that the return significant wave heights of two methods are different, which may be mostly caused by the difference in the sampling theory. In the POT method, a flexible sampling window is used to extract the extreme sample. Thus, the number and representativeness of extreme samples can be guaranteed in the North, and the return significant wave height estimated by the POT/GPD method may be relatively reliable in this direction.

The remainder of the article is structured as follows. In Section 2, the extreme value analysis method, including the sampling theory and distribution equation, is provided. Section 3 shows a 22-year hindcast database in the Yellow Sea and 4 study sites in this area. In Section 4, the fixed window method is revisited in the Yellow Sea; directional declustering is analysed within the independent sample; and extreme significant wave heights are estimated in a main directional bin. In Section 5, the conclusions are presented.

2. Background

This section describes the sampling theories of the POT and AM methods and exhibits the distribution equations of the GPD and Gumbel models.

2.1. POT/GPD Method

In the POT method, the peak significant wave height is extracted over the threshold, *u*, as the extreme sample for extrapolation. Considering the significant role of the threshold for this method, this value should be prudently selected [31].

With the extreme sample extracted by the POT method, the GPD model can be used to extrapolate the extreme significant wave height, whose distribution function is expressed as follows [32]:

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

where Hs_u represents the peak excesses over u; σ represents the scale parameter; and k represents the shape parameter. In this study, the maximum likelihood estimation method [33] is employed to estimate σ and k.

The return significant wave height with the *i*-year return period, H_{s_i} , is expressed as follows:

$$Hs_{i} = \begin{cases} u + [(\lambda i)^{k} - 1]\sigma/k & k \neq 0\\ u + \sigma ln(\lambda i) & k = 0 \end{cases}$$
(2)

where λ represents the annual mean number of extreme samples, which is expressed as follows:

$$\lambda = \frac{N}{N_T} \tag{3}$$

where N represents the number of extreme samples and N_T represents the dataset length.

2.2. AM/Gumbel Method

In addition to the POT/GPD method, the AM/Gumbel method is widely used to estimate the extreme significant wave height. The AM method extracts the annual maximal significant wave height as the extreme sample. As a common probabilistic model, the Gumbel model is used to fit this sample, whose distribution function is expressed as follows [30]:

$$F(Hs^*) = exp(-exp(-(Hs^* - \beta)/\alpha))$$
(4)

where Hs^* represents the annual maximal significant wave height, α and β represents the scale parameter and location parameter, respectively. By the maximum likelihood estimation method, α and β can be estimated.

Hs_i is defined as follows:

$$Hs_i = \beta + \alpha y_i \tag{5}$$

where $y_i = -ln(-ln(1 - 1/i))$.

3. Initial Database and Study Site

To analyse the extreme wave in the Yellow Sea, a 22-year (1990–2011) hindcast of significant wave heights in this area is determined as the initial database. Liang et al. [11] simulated this database by the Simulating WAves Nearshore (SWAN) model [34]. This model has been widely used in the wave simulations at the global [35], regional [36] and local [37] scales, and most of the results show that these simulations are reliable [38]. In the simulation of Liang et al. [11], the hindcasted significant wave height, which has a spatial resolution of 0.1' and a temporal resolution of 3 h, has been fully calibrated and validated. The results show that this simulation is also reliable.

In the Yellow Sea, 4 locations (shown in Figure 1) are determined as the study sites. At these sites, a 22-year time series hindcast is studied to estimate the extreme significant wave height. It can be noticed that the independent and identically distributed samples cannot be directly extracted from the time series database, i.e., independent wave events and different physical processes cannot be directly identified in this database. To extract the independent and identically distributed samples, the fixed time window method and directional declustering are employed in this study, respectively.



Figure 1. Bathymetry of the study region and four study sites (black triangles).

4. Estimation of Extreme Waves

4.1. Fixed Window Method

In an ideal condition, the peak significant wave height in every wave event is determined as the independent sample. However, in a real sea state, the wave process is complex, and the duration of wave events may vary considerably. Thus, the individual wave event is difficult to identify directly. In the Yellow Sea, Gao et al. [17] have analysed the meteorological characteristics and studied the extraction of the independent sample from the time series initial database. By employing the fixed window method in this area, the independent sample is extracted in a fixed time window. In this method, the independent sample is highly dependent on the time window. If a short time window is determined, the selected sample may come from one wave event; thus, the independence of the sample cannot be guaranteed. In contrast, some wave events close to strong wave events may be ignored; thus, the number of samples cannot be guaranteed. In the Yellow Sea, Gao et al. [17] suggested that the time window should range from three d to five d. The large independent samples under fixed time windows of three d and five d are the same, and the largest different value in two groups of independent samples is obviously smaller than the largest independent sample. To guarantee the extraction of the independent sample (especially the large independent sample), Gao et al. [17] recommended a fixed time window of five d.

In this study, the fixed window method is revisited in the Yellow Sea. Within every window of five d, the peak significant wave height in the identified storm is determined as the independent sample. The peak significant wave height with a small proximity to a large one is rejected, based on a predefined minimum separation time (72 h). To validate the extracted samples, these samples are analysed in the time series initial database. In Figure 2, the largest four storms in a 22-year period are shown in the 720-h (30-day) period. At location S1, the peak significant wave heights in storms 1, 2, 3 and 4 are 7.19 m, 6.94 m, 6.47 m and 6.32 m, respectively. It can be observed that there are some small wave events in addition to the identified storms. Section 4.3 presents a threshold of 4.16 m at location S1. This means that these storms are properly identified, and the omission of small wave events is reasonable. In Figure 3, the fifth largest storm in a 22-year period is also shown in a 720-h period. At location S1, the peak significant wave height in storm 5 is 6.29 m. It can be observed that there is a small storm in addition to storm 5. The peak significant wave height of this small storm is 4.36 m, and both storms exceed the threshold of 4.16 m. Although two storms are identified in a 720-h period, they are properly extracted due to a long storm interval. The small storm and storm 5 are observed in the second and fourth windows, and the time interval between their peak significant wave heights is 189 h (7.875 d).

In the time series initial database, the consecutive significant wave heights are analysed. It can be concluded that the peak significant wave heights in the strong storms at the four study sites can mostly be extracted by a fixed time window of five d. However, for moderate and small storms, lost and false extractions of independent samples may exist. Considering that the influence of moderate and small independent samples is obviously weaker than that of the large independent sample on the estimation of extreme significant wave heights, these lost and false extractions may be ignored. Thus, the fixed window method may be suitable for extracting the independent sample in the Yellow Sea, and the extracted samples may be suitable for studying directional declustering in this area.



Figure 2. Time series significant wave heights of location S1 in the 720-h period, covering (**a**) storm 1, (**b**) storm 2, (**c**) storm 3 and (**d**) storm 4.



Figure 3. Time series significant wave heights of location S1 in a 720-h period, covering storm 5.

4.2. Directional Declustering

At location S1, the 22-year time series significant wave height is divided into eight directional bins by analysing the wave direction. Figure 4 shows the percentage of this hindcast in every bin. Most of the significant wave heights are observed in the North (25%) and South (21%). In addition to this information, Figure 4 shows the distribution of significant wave heights in every bin. It can be observed that the number and value of large significant wave heights are obviously larger in the North than those in the South. Thus, the main direction of waves (especially large waves) at location S1 is North.



Figure 4. The rose plot of significant wave heights from 1990 to 2011 at location S1.

In Section 4.1, the independent sample has been extracted by the fixed window method. At location S1, this sample is divided into eight directional bins by analysing the wave direction. Figure 5 shows

the percentage of the independent sample in every bin. Most of these samples are observed in the North (44%). Although the percentage of significant wave heights in the South (shown in Figure 4) is large, the percentage of independent samples in this direction is relatively small (17%). In addition to this information, Figure 5 shows the distribution of independent samples in every bin. It can be observed that the number and value of large independent samples are obviously large in the North. Thus, the main direction of independent samples (especially large independent samples) at location S1 is North. In this direction, the largest value of the independent sample is 6.29 m, and the number of independent samples is 688. Compared with the value of the independent sample in the other directional bins, this value in the North may be sufficiently high. In addition, the number of independent samples in the North may be sufficiently large, which satisfies the study of Mazas and Hamm [33], i.e., the annual mean number of extreme samples is suggested to be around five when the length of the initial database is 20 years. Thus, the North is selected as the main directional bin to study the extreme significant wave height at location S1.



Figure 5. The rose plot of independent samples from 1990 to 2011 at location S1.

By analysing the 22-year time series significant wave heights and independent samples at the other three study sites, similar conclusions can be obtained. The main direction of waves (especially large waves) and main direction of independent samples (especially large independent samples) are North. At the other three study sites, this direction is also selected as the main directional bin to study the extreme significant wave height.

4.3. Return Significant Wave Height

At location S1, the extreme significant wave height is analysed in the North. To extract the extreme sample from 688 homogenous samples, the POT method is employed. In Section 2.1, the theory of this method shows that the extracted extreme sample is highly dependent on the threshold. To select a suitable threshold, the GPD parameter plot [39] is employed. By fitting the GPD over a range of candidate thresholds, the corresponding shape parameter and modified scale parameter $(\sigma 1 = \sigma - ku)$ [31] can be estimated. By identifying the stability of these parameters, a suitable threshold can be determined. In fact, the estimated parameters cannot be exactly constant due to the sampling variability. However, these parameters should be stable after allowing for the sampling error [31]. When the estimated parameters remain nearly constant, the suitable threshold can be defined as the lowest threshold within the stable threshold range. At location S1, the candidate threshold is set, ranging from 3.2 m to 5.0 m with a threshold interval of 0.02 m. The corresponding shape parameter and modified scale parameter are shown in Figure 6. It can be observed that 4.16 m is a suitable threshold. To complement the analysis of the GPD parameter plot and validate the selected threshold, the sensitivity of the return significant wave height to the threshold is studied. By analysing the influence of the excluded sample on the return significant wave height, this method can be used to test the rationality of candidate thresholds. In Figure 7, the return significant wave heights with the return periods of the 50-year, 100-year, 150-year and 200-year are relatively stable when the threshold is larger than 4.16 m. Thus, the selected threshold is reasonable for sampling.

By using the selected threshold, 86 homogenous samples (shown in Figure 8) are extracted as the extreme sample in the North. The corresponding annual mean number of extreme samples is 3.91, which is in accordance with the study of Mazas and Hamm [33] on the association between this number and the dataset length, and close to the study of Gao et al. [17] on this number (4 to 6) in the Yellow Sea. Fitting the GPD model with the extreme sample, the return significant wave heights with the return periods of the 50-year, 100-year, 150-year and 200-year are estimated, which are 5.94 m, 6.12 m, 6.21 m and 6.27 m, respectively. To assess the uncertainty of these values, the likelihood method [40] is employed, which reparametrizes the likelihood in terms of the unknown quantile and uses profile likelihood arguments to construct a 95% confidence interval. For the return periods of the 50-year, 100-year, 150-year and 200-year, the confidence intervals are (5.71 m, 6.46 m), (5.86 m, 6.83 m), (5.94 m, 7.05 m) and (5.97 m, 7.20 m), respectively. Comparing the widths of these intervals with the corresponding return significant wave heights, the relatively small widths show that the return significant wave heights are acceptable. To assess the fit result of the GPD model with the extreme sample, the probability plot at location S1 (Figure 9) is analysed. It can be observed that the differences between the empirical and model values are generally few, which implies that the extreme significant wave height is extrapolated by a good fit. Consequently, the return significant wave height in the North is reliable.



Figure 6. The modified scale parameter (**above**) and shape parameter (**below**) in relation to the thresholds (3.2–5.0 m) at location S1.



Figure 7. Sensitivity of the return significant wave heights to the thresholds (3.2–5.0 m) at location S1.



Figure 8. Extreme samples extracted by the peak over threshold (POT) method at location S1.



Figure 9. The probability plot for the POT/generalized Pareto distribution (GPD) method at location S1.

At location S1, the extreme significant wave height is also analysed in the North by the AM/Gumbel method. The AM method takes 22 annual maximal significant wave heights (shown in Figure 10) from 1990 to 2011 as the extreme sample. Fitting this sample, the Gumbel model is employed to estimate the return significant wave heights in the return periods of 50-year, 100-year, 150-year and 200-year, which are 8.34 m, 9.03 m, 9.43 m and 9.71 m, respectively. To assess the uncertainty of these values, the confidence intervals are also estimated. For the return periods of the 50-year, 100-year, 150-year and 200-year, these intervals are (7.01 m, 9.91 m), (7.36 m, 10.63 m), (7.73 m, 11.18 m) and (8.02 m, 11.54 m), respectively, which are wider than the confidence intervals of the POT/GPD method. To assess the fit result of the Gumbel model with the extreme sample, the probability plot at location S1 (Figure 11) is analysed. It can be observed that the differences between the empirical and model values are considerably large, which imply an unsatisfactory fit in the estimation. Consequently, the return significant wave height in the North may be unreliably estimated by the AM/Gumbel method.



Figure 10. Extreme samples extracted by the annual maxima (AM) method at location S1.



Figure 11. The probability plot for the AM/Gumbel method at location S1.

Comparing the estimations of extreme waves in the POT/GPD method with those in the AM/Gumbel method, their return significant wave heights, probability plots and confidence intervals present considerable differences at location S1. Because the value and number of extreme samples in the POT method are very different from those in the AM method, these estimation differences may be attributed to the sampling method. In the POT method, the annual mean number of extreme samples is 3.91, which is obviously larger than that (an annual mean number of 1) in the AM method. It can be derived that the POT method makes the full use of homogenous samples. However, the AM method only extracts a constant number of extreme samples (i.e., 1) in the yearly scale. In the POT method, the minimal extreme sample is 4.19 m, which is obviously higher than that (0.88 m) in the AM method. It can be derived that the POT method can ensure the representativeness of the extreme sample when the selected threshold is suitable. However, the AM method does not consider the obvious variation in the yearly distribution of homogenous samples. Thus, some small homogenous samples may be selected in the extreme sample. In the omnidirectional estimation of extreme significant wave heights, this false selection may be unobvious. Thus, the AM method has been widely used in the estimation of extreme significant wave heights [40], especially in the regional estimation of extreme significant wave heights [41]. However, for an estimation in a main direction (such as North at location S1), this false selection cannot be ignored, because the limitation of the AM method (i.e., a fixed sampling window of 1 year) may be exacerbated by a yearly variation of one physical process in this direction. In this condition, the minimal extreme sample may be obviously smaller than the maximal extreme sample, and the minimal extreme sample may be too small to represent the extreme wave event. Thus, the extreme sample extracted by the AM method in a directional bin may be unreliable.

By estimating the extreme waves at the other three study sites, similar conclusions can be obtained. Because the POT method can ensure the representativeness and number of extreme samples when the threshold is reasonable, the POT/GPD method is selected for estimating the extreme significant wave height in the North. In Table 1, the thresholds identified by the GPD parameter plot and the return significant wave heights in the return periods of the 50-year, 100-year, 150-year and 200-year are shown. At locations S2, S3 and S4, the identified thresholds are 4.62 m, 4.50 m and 4.82 m, respectively; and the numbers of extreme samples exceeding these thresholds are 105, 96 and 109, respectively. These numbers also accord with the association between the number of extreme samples and the dataset length [33]. Extrapolated by the GPD model, the return significant wave heights in the return periods of the 50-year, 100-year, 150-year and 200-year are 7.45 m, 7.71 m, 7.83 m and 7.93 m at location S2; 6.70 m, 6.90 m, 6.98 m and 7.06 m at location S3; and 7.60 m, 7.84 m, 7.94 m and 8.03 m at location S4.

Location	Method	Threshold (m)	50-year (m)	100-year (m)	150-year (m)	200-year (m)
S1	POT/GPD	4.16	5.94	6.12	6.21	6.27
			(5.71, 6.46)	(5.86, 6.83)	(5.94, 7.05)	(5.97, 7.20)
	AM/Gumbel	/	8.34	9.03	9.43	9.71
			(7.01, 9.91)	(7.36, 10.63)	(7.73, 11.18)	(8.02, 11.54)
S2	POT/GPD	4.62	7.45	7.71	7.83	7.93
			(7.14, 8.10)	(7.36, 8.58)	(7.49, 8.85)	(7.56, 9.03)
	AM/Gumbel	/	9.14	9.83	10.24	10.53
			(7.74, 10.52)	(8.20, 11.38)	(8.54, 11.94)	(8.71, 12.34)
S3	POT/GPD	4.50	6.70	6.90	6.98	7.06
			(6.45, 7.20)	(6.64, 7.57)	(6.73, 7.76)	(6.79, 7.90)
	AM/Gumbel	/	8.27	8.90	9.26	9.52
			(6.93, 9.63)	(7.40, 10.37)	(7.63, 10.88)	(7.81, 11.26)
S4	POT/GPD	4.82	7.60	7.84	7.94	8.03
			(7.32, 8.29)	(7.52, 8.75)	(7.62, 9.01)	(7.70, 9.20)
	AM/Gumbel	/	9.10	9.71	10.06	10.31
			(7.84, 10.46)	(8.25, 11.20)	(8.48, 11.61)	(8.67, 11.98)

Table 1. Return significant wave heights in the North at four study sites.

To study the necessity of sample homogeneity, the return significant wave height is extrapolated based on the independent sample. At location S1, the GPD model is directly fitted to the independent sample exceeding 4.16 m. The return significant wave heights with the return periods of the 50-year, 100-year, 150-year and 200-year are estimated, which are 6.50 m, 6.83 m, 7.01 m and 7.13 m, respectively. It can be observed that these return significant wave heights are larger than the return significant wave heights in the North, because more samples are included in the extrapolation. For the return periods of the 50-year, 100-year, 150-year and 200-year, the confidence intervals are (6.15 m, 7.32 m), (6.39 m, 8.00 m), (6.50 m, 8.41 m) and (6.60 m, 8.74 m), respectively. These confidence intervals are wider than the confidence intervals in the North. Although more samples are used in the omnidirectional estimation, the uncertainty of the return significant wave height is great, which reveals the significant role of sample homogeneity.

5. Conclusions

In the Yellow Sea, directional declustering is studied to estimate the extreme significant wave height. Considering the meteorological characteristics in this area, a time series hindcast with a 22-year span (1990 to 2011) is determined as the initial database. To extract the independent sample from this database, a fixed window method is revisited in the Yellow Sea. The validation analyses of extracted samples in a 22-year time series show that a time window of five d is reasonable. The peak significant wave heights of strong storms can mostly be extracted by this window, and these samples are crucial for extrapolating extreme significant wave heights.

Analysing the 22-year time series significant wave heights and independent samples in eight directional bins, these values (especially large values) are mostly observed in the North. Thus, this direction is selected as the main directional bin for estimating the directional extreme significant wave height. In the North, the POT and AM methods are employed to extract the extreme sample from the homogenous sample, respectively. Accordingly, the GPD and Gumbel models are employed to extrapolate the extreme value, respectively. The comparison results show obvious differences, which may be attributed to the sampling method. In the main directional bin, a fixed sampling window of one year may not ensure the number and representativeness of extreme samples. For example, the minimal extreme sample may be obviously smaller than the maximal extreme sample, and the minimal extreme sample may be too small to represent the extreme wave event.

Benefiting from the flexible sampling window of the POT method, the return significant wave height is reasonable within a certain return period, when the threshold is suitable. However, when the return period is far from the dataset length, the uncertainty of the return significant wave height cannot be ignored due to a limited initial database. Benefiting from a simple sampling process of the AM method, the extreme sample may be robust for assessing the extreme significant wave height, especially for assessing the regional extreme significant wave height, when the return period is close to the dataset length. However, the limitation of a fixed sampling window cannot be ignored when the number and value of homogenous samples (such as homogenous samples at four study sites in the Yellow Sea) vary greatly in a yearly scale. Consequently, the POT/GPD method is employed for estimation in the North, based on the homogenous sample extracted by directional declustering. In fact, the directional spectrum can also be employed to extract the sea states from different directions, because this spectrum can reveal energies from multiple directions. Further studies are suggested to partition the directional spectrum and isolate the directional system.

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