



# Extreme Wave Height Estimation for Energy Resource Classification

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## Introduction

Significant wave heights occurring at 50-year return periods on average,  $H_{S50}$ , are important metrics used to evaluate and classify the extreme environmental wave loads to design wave energy converters (Fig. 1) [IEC/TS 62600-2]. They are also used to evaluate and classify risks at wave energy project sites with respect to opportunities for wave energy extraction,  $H_{S50}/H_{Smean}$ , (Fig. 2) [Neary, 2017].

There are two common methods for estimating  $H_{S50}$ : the annual maxima (AM) and the peak-over-threshold (POT) method [DNV, 2014]. The AM method [Coles, 2001] fits the yearly maxima  $H_S$  to a Gumbel distribution:

$$F(x) = e^{-e^{-\frac{(x-\mu)}{\beta}}}$$

It is simple to implement and readily automated with no user input requirements, but requires a minimum historical record of approximately 20 years [DNV, 2014].

The POT method [e.g., Ferreira and Guedes Soares, 1998] uses a much larger sample population of extreme values than the AM method, but requires selection of a threshold  $H_S$ , denoted  $v$ , and tests to ensure independence of the samples and how well the extreme distribution is modeled. A special type of Generalized Pareto distribution that is commonly used is the exponential distribution:

$$F(x) = 1 - e^{-\delta x}$$

The threshold for this method,  $v$ , needs to be chosen with care. If too low, the asymptotic law of the Generalized Pareto distribution is violated. If too high, the sample population is reduced and less samples remain to fit a distribution. Guidance for threshold selection is varied, and there is no accepted standard. A variety of tests and criteria are used, e.g., multiple Goodness-of-Fit (GoF) tests and visual evaluation of Quantile-Quantile (QQ) plots [e.g. Ferreira and Guedes Soares, 1998]. As a result, threshold choices can vary significantly depending on what tests and criteria are used, and which ones are more heavily weighted. This introduces user bias, which can be further exacerbated when test results are inconclusive. Some have even automated threshold selection to reduce user bias [e.g. Thompson et. al., 2009]. Although it is widely known that  $H_{S50}$  is sensitive to threshold choice [e.g. Li et al, 2012], we are unaware of any comprehensive sensitivity study over multiple wave sites within a regional wave climate.

In summary, while the POT method has clear advantages at sites with a short historical record, there is still no consensus on threshold selection, which raise questions about its consistency and credibility. Threshold choice can be subjective and biased when tests are inconclusive. The AM method, therefore, may be the most suitable method for estimating  $H_{S50}$  when the sites historical  $H_S$  record spans decades.

## Study Goals

In this study, we compare results from AM and POT methods for wave sites along the US West Coast to guide selection of suitable  $H_{S50}$  estimation methods for wave energy classification. Methods are first described for threshold selection among three POT methods and criteria for assessing user selection bias. Threshold and  $H_{S50}$  values from these different methods are then compared in scatter plots, which illustrate the sensitivity of the  $H_{S50}$  estimates to threshold choice. Following our analysis of user bias, main findings and concluding remarks are summarized.

## Methods: Threshold Selection

For the POT method, three different methods for threshold selection are examined to evaluate its effect on the  $H_{S50}$  estimate sensitivity and user bias (Table 1). For all methods, independence of samples was ensured using the Autocorrelation Function (ACF). As a 30-year historical record of  $H_S$  values are used for our study sites, the  $H_{S50}$  estimated using the AM method serve as reference values for all comparisons.

Table 1. POT Threshold Selection Methods

Selection Method	Manual/Automated	Tests	Criteria
MQQR	Manual	QQ Plots, WWR	Visual Examination, p-value (WWR)
MGoFEx	Manual	GoF, Mean Excess	Visual Examination, p-value (GoF)
AEx	Automated	Mean Excess	p-value

When manually selecting  $H_S$  thresholds for our study, quantile-quantile plots (QQ Plots) are used to ensure that the data fit the assumed distribution; Wald-Wolfowitz Runs tests (WWR) are applied to ensure the data samples are independent [Bradley, 1968]; and mean excess and traditional goodness-of-fit tests (GoF) for exponential distributions, including Pearson's Chi-Squared and Anderson-Darling tests are conducted [Ferreira and Guedes Soares, 1998].

When automating threshold selection, candidate thresholds ranging from the median  $H_S$  value,  $v_1$ , to the 98<sup>th</sup> percentile  $H_S$  value,  $v_n$ , are identified and used in the exponential distribution model. First order differences are calculated from the mean, or shape parameter from the exponential distribution,  $\mu$ , for all candidate thresholds. It is then determined if these differences fit a standard normal distribution using Pearson's Chi-Squared test. Differences are sequentially removed from this set, and Pearson's Chi-Squared test is repeated until a standard normal distribution is achieved. The chosen threshold value is then  $v_{n-1}$  [Thompson et. al. 2009]

## Data

In this study, AM and POT methods were applied to simulated hourly  $H_S$  time series generated from WAVEWATCH III [NOAA] hindcasts at 85 wave sites selected along the West Coast. These hindcasts cover 30 years of data, from January 1979 to December 2009. A heatmap of the  $H_{S50}$  values calculated from the hindcast data using the Annual Maxima method is shown in Fig. 1 insert.

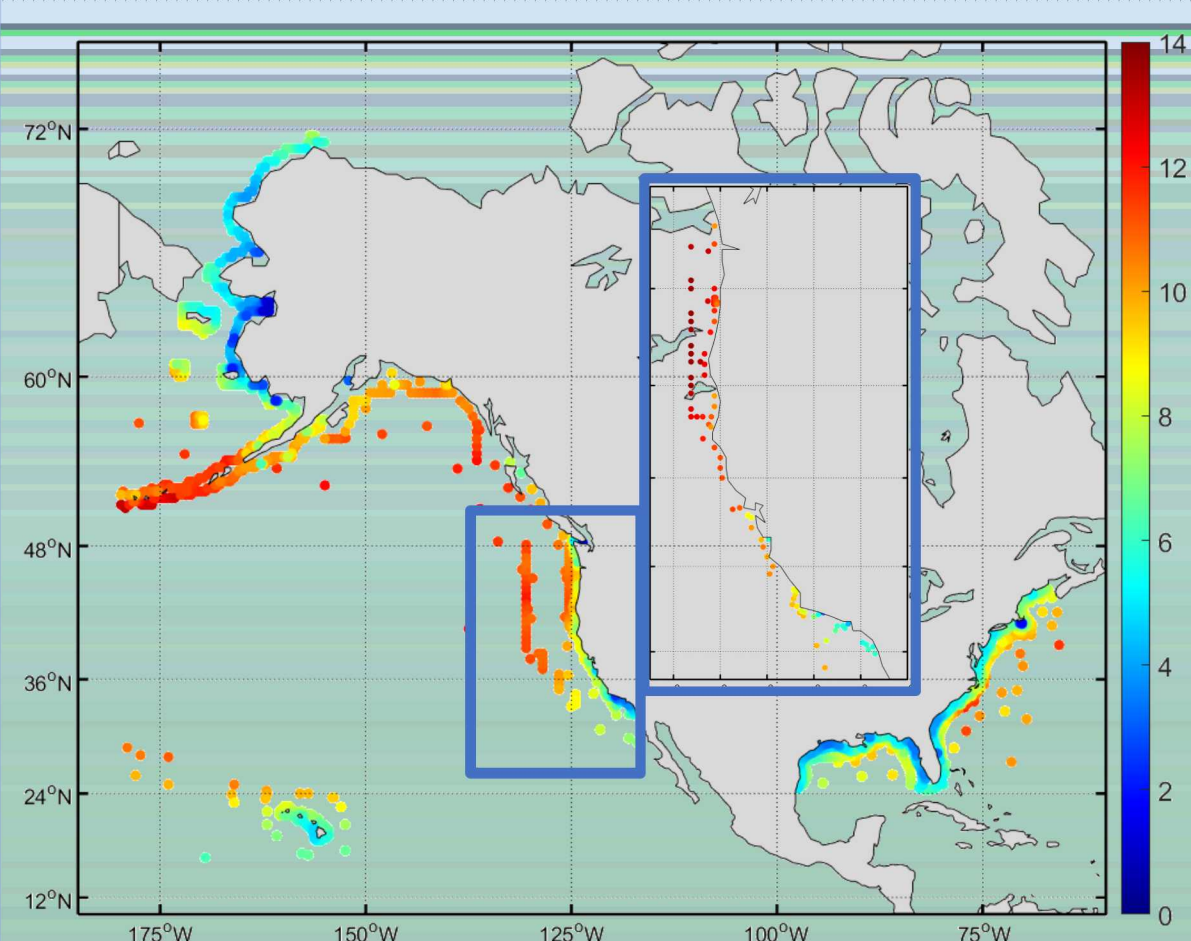


Fig. 1.  $H_{S50}$  values calculated from the AM method. The insert shows the 85 study sites.

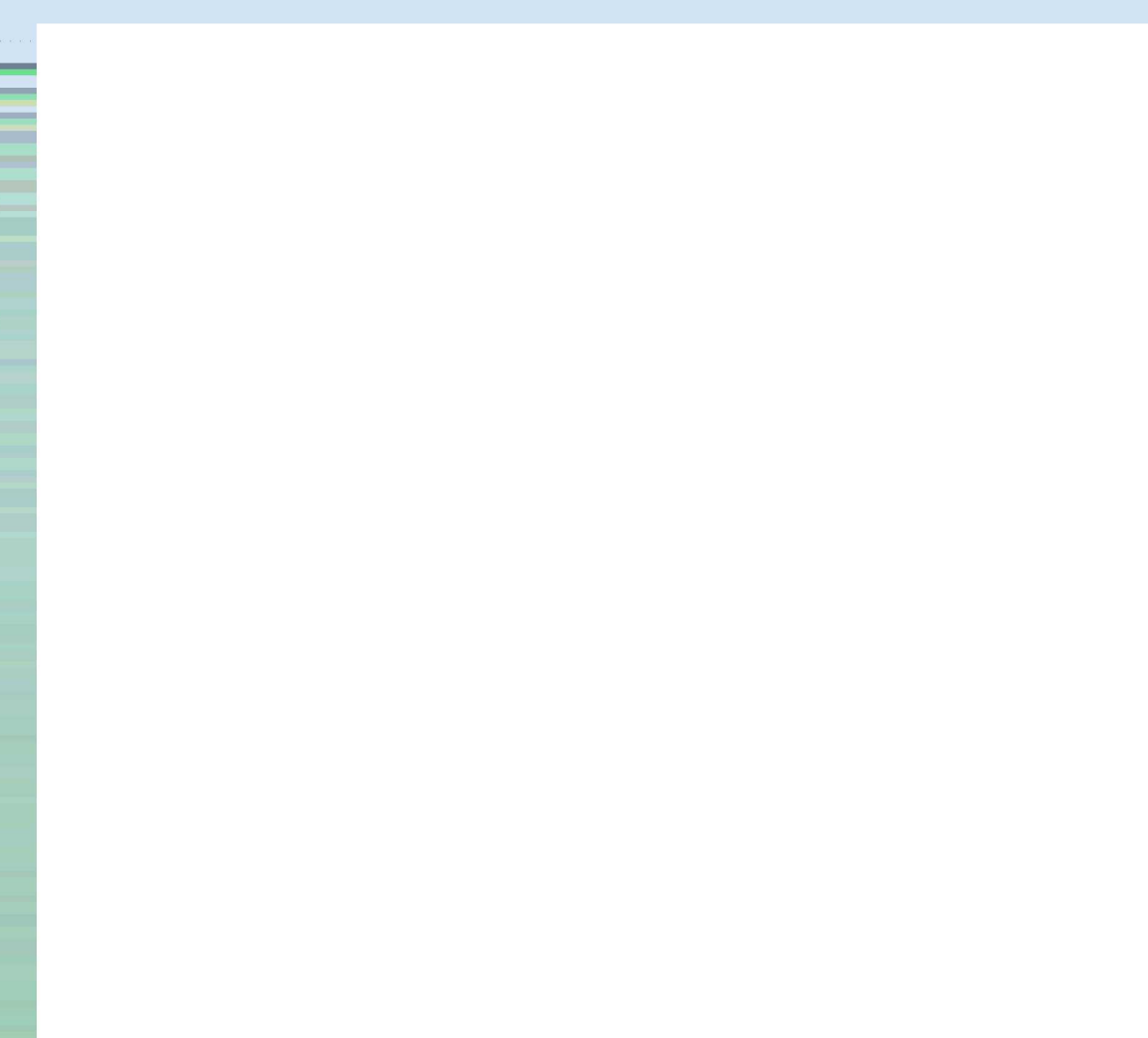


Fig. 2. Relative Risk Ratio Class Map for the US Coast calculated from the AM method.

## Methods: User Bias

For studying the sensitivity of the  $H_{S50}$  value to the threshold and user bias, we compare the two manual POT threshold selection methods in Table 1, MQQR and MGoFEx. For these methods, the level of user uncertainty in threshold selection was scored as 1 – objective and clearly guided by the tests, 2 – partially guided by the tests, and 3 – subjective or not clearly guided by the tests.

Comparing the results between the MQQR and Annual Maxima (Fig. 3.) showcase strong agreement between the  $H_{S50}$  values. However, when looking at the results achieved using the MGoFEx and Annual Maxima (Fig. 4.) show that, for values of  $H_{S50} > 6m$ , the MGoFEx results tend to be much larger, in some cases by as much as 1.5m. For values of  $H_{S50} < 6m$ , though, the AM method returns larger values of  $H_{S50}$ . This trend is also visible in the graph of the results from the AEx and AM methods (Fig. 5.).

Compare these results to the graphs of the corresponding threshold values (Fig. 6,7,8), which show that the thresholds in MQQR tend to be much larger than the thresholds in both MGoFEx and AEx. The thresholds chosen in MGoFEx and AEx are fairly similar to each other. The larger thresholds in MQQR generate  $H_{S50}$  values closer to the values from the AM method, and the smaller thresholds in MGoFEx and AEx generate more deviation in  $H_{S50}$  values. This sensitivity between threshold choice and  $H_{S50}$  value is in line with previous literature [Li et. al. 2012].

Between the manual methods MQQR and MGoFEx, threshold choice varies due to the prioritized tests to check and user bias. Table 2 showcases the objectivity ratings among the 2 tested methods. For both methods, relying on graphical methods resulted in more than 50% of all sites having at least some form of underlying subjectivity or uncertainty in the threshold choice.

Table 2. User Bias Results

Method	1 (Objective)	2 (Mixed)	3 (Subjective)
MQQR	39 (45.88%)	30 (35.29%)	16 (18.82%)
MGoFEx	37 (45.53%)	36 (42.35%)	12 (14.12%)

## Conclusions

$H_{S50}$  estimates are sensitive to threshold choice, and, therefore, vary significantly depending on the tests and criteria used to guide threshold selection. Also, a significant amount of user bias is introduced when tests conflict or are inconclusive. Until these discrepancies can be resolved and there is consensus on a standard method, threshold selection methods should be carefully documented and used with caution. Given these drawbacks, the AM method is an attractive choice when sufficient historical record exists.  $H_{S50}$  estimates using the AM method are in particularly good agreement with those using the POT MQQR method. Advocates of POT methods could justify their use because they generally estimate larger, more conservative,  $H_{S50}$  values.  $H_{S50}$  values using the AM method are generally significantly lower at higher values above approximately 6m when using the other POT methods (MGoFEx, AEx). However, design standards (e.g. DNV 2014) do not require using POT methods when a sufficient historical record exists. If studies can show that the mean excess method, which tends to estimate high  $H_{S50}$  values in this range, guides a more accurate threshold choice than methods that do not use this test, e.g., MQQR, this would be a more sound basis for its use.

## Results

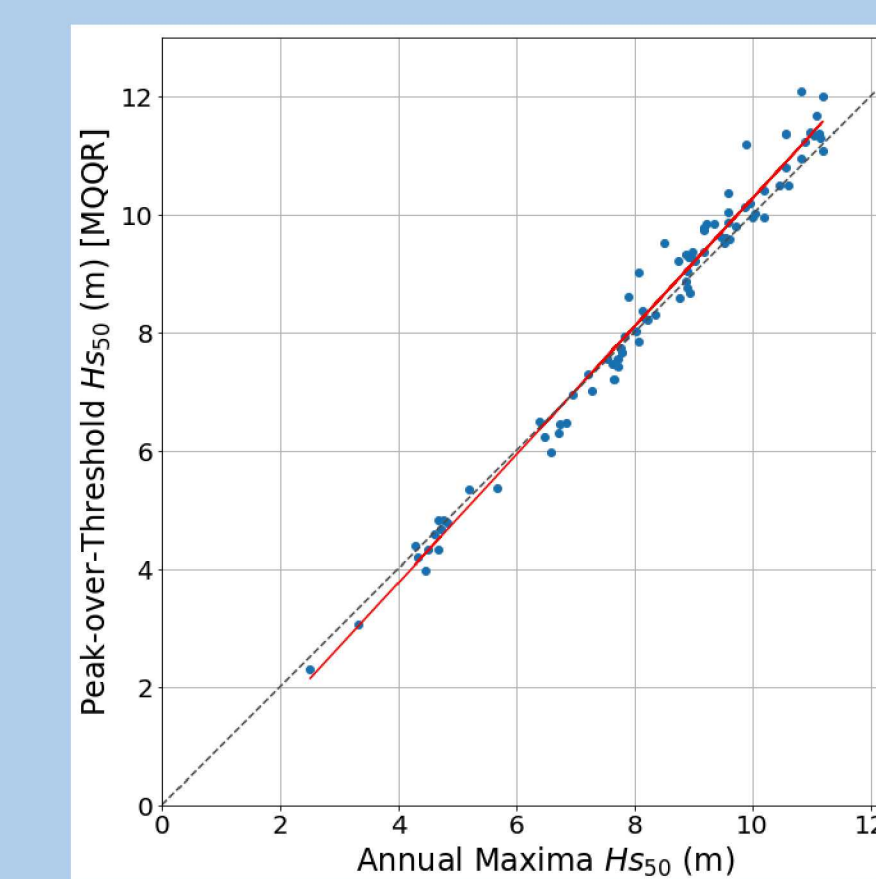


Fig. 3. MQQR vs. AM  $H_{S50}$  Values

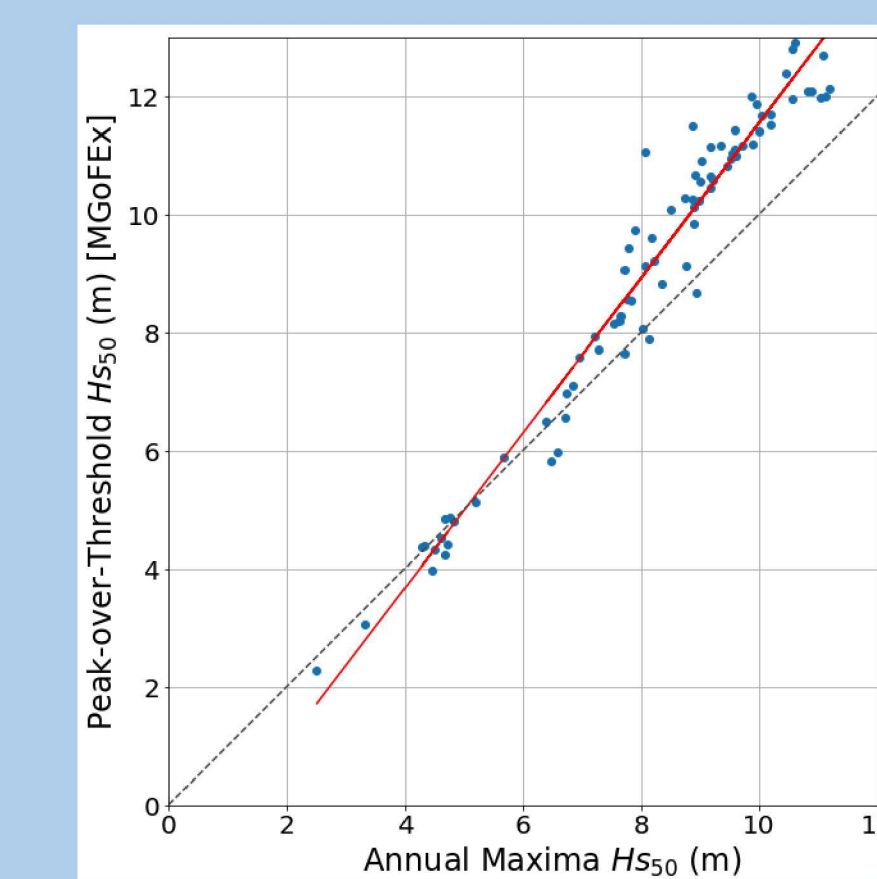


Fig. 4. MGoFEx vs. AM  $H_{S50}$  Values

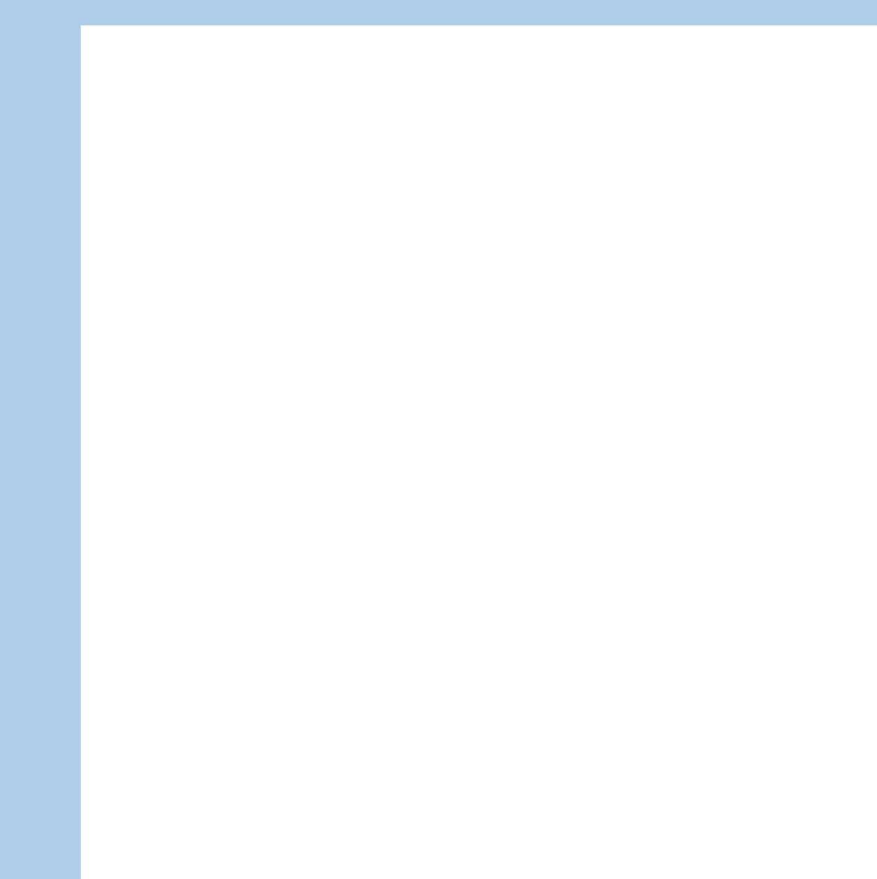


Fig. 5. AEx vs. AM  $H_{S50}$  Values

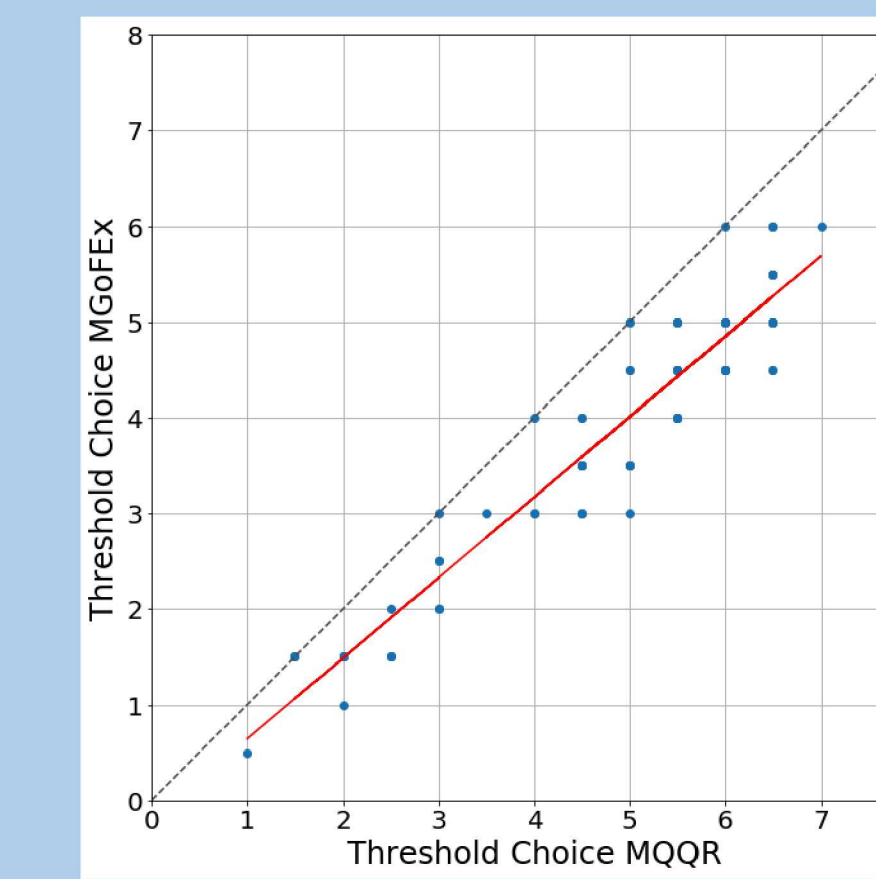


Fig. 6. MQQR vs. MGoFEx Threshold Choice

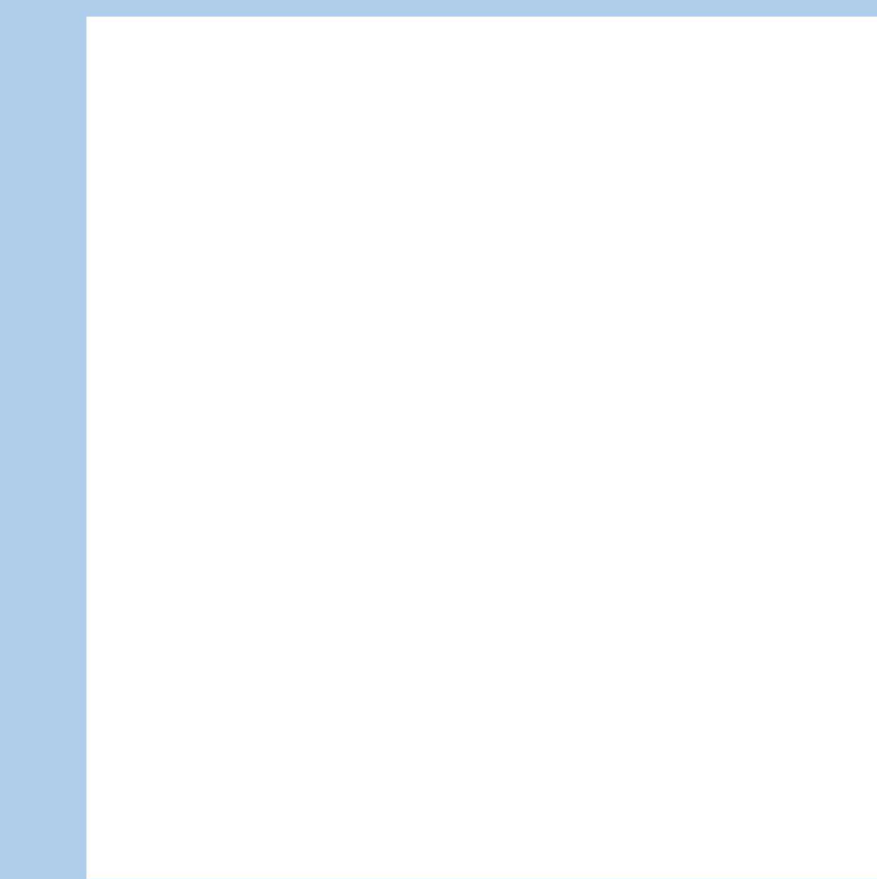


Fig. 7. MQQR vs. AEx Thresholds

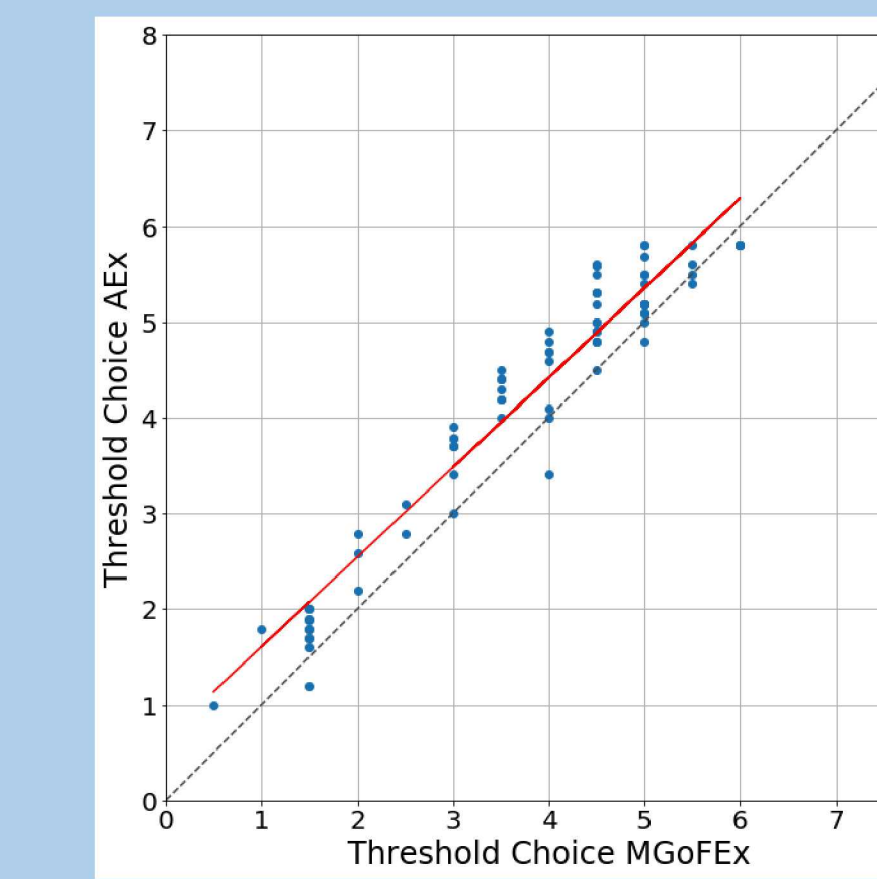


Fig. 8. MGoFEx vs. AEx Thresholds

## References

- Coles, S. "An Introduction to Statistical Modeling of Extreme Values." 2001. Springer.
- Bradley, J. "Distribution-free Statistical Tests." 1968. Prentice-Hall.
- DNV, 2014. Recommended Practice – DNV-RP-C205 Environmental Conditions and Environmental Loads. Technical Report. Det Norske Veritas
- Ferreira J.A., Guedes Soares C. "An Application of the Peaks Over Threshold Method to Predict Extremes of Significant Wave Height." ASME. *J. Offshore Mech. Arct. Eng.* 1998, vol 120, no.3, pp. 165-176.
- IEC/TS 62600-2: Marine energy – Wave, tidal and other water current converters – Part 2: Design requirements for marine energy systems. Edition 1.0, 2016-08.
- Li, F. et. al. "A Comparison of Extreme Wave Analysis Methods with 1994-2010 Offshore Perth Dataset." *Coastal Engineering*, 2012, vol. 69, pp. 1-11.
- Neary, V. et. al. "Classification systems for Wave Energy Resources and WEC Technologies." European Wave and Tidal Energy Conference, 2017.
- Thompson, P. et. al. "Automated Threshold Selection Methods for Extreme Wave Analysis." *Coastal Engineering*, 2009, vol. 59, pp. 1012-1021
- WAVEWATCH III® Hindcast and Reanalysis Archives. Natl Ocean Atmos Adm n.d. <http://polar.ncep.noaa.gov/waves/hindcasts/>.