Manuscript Details

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Title	Joint description of waves and currents applied in a simplified load case
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Abstract

In order to perform a more accurate analysis of marine structures, joint probability distributions of different metocean parameters have received an increasing interest during the last decade, facilitated by improved availability of reliable joint metocean data. The main objective of this article is twofold; first to establish a joint distribution of significant wave height and current speed and then to assess the possible conservatism in the Norwegian design standard by applying this joint distribution in a simplified load case. As there still seems to be no general consensus with regard to the approach of estimating the joint probability distributions of metocean parameters, a general overview of recent studies exploring different joint models for metocean parameters is first presented. Based on simulated current data and NORA10 wave data, a joint model for significant wave height and current speed at one location in the northern North Sea is presented. Since episodes of wind-generated inertial oscillations is the governing current conditions at this location, a conditional joint model with current speed conditional on significant wave height is suggested. A peak-over-threshold approach is selected and the significant wave height is found to be very well modelled by a 2-parameter Weibull distribution for significant wave height exceeding 8 m, while a log-normal distribution describes the current speed well. This model is used to Monte-Carlo simulate joint significant wave heights and current speeds for periods corresponding to the ultimate and accidental limit states (ULS and ALS), i.e. 100 and 10 000 years. The possible conservatism in the Norwegian design standard is assessed by a simplified case study. The results give a clear indication that the Norwegian design standard in not necessarily conservative, neither at ULS nor ALS level.

Keywords Waves; Currents; Joint probability distribution; Northern North Sea; NORSOK N-003

Corresponding Author Kjersti Bruserud

Corresponding Author's Institution Statoil / NTNU

Order of Authors Kjersti Bruserud, Sverre Haver, dag myrhaug

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Mrs. Kjersti Bruserud
STATOIL ASA, Norwegian University of Science and Technology
E-mail: kjbrus@statoil.com
Phone: +47 95 75 79 46

October 30th 2017

Editor of Marine Structures
Professor Torgeir Moan

Dear Professor Torgeir Moan,

Please find enclosed the revised manuscript "Joint description of waves and currents applied in a simplified load case", submitted for publication in Marine Structures.

The manuscript has been revised according to the concerns and suggestions of the reviewers. The review has been thorough and the reviewers have provided detailed comments which increased the quality and relevance of this paper significantly. All comments have been accommodated and implemented.

With thanks and regards,

Kjersti Bruserud
Kjersti Bruserud

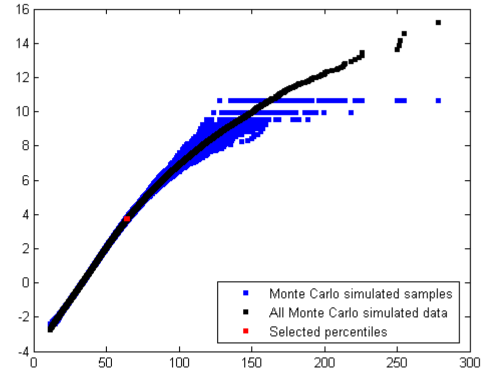
Manuscript Number MAST_2017_228: Joint description of waves and currents applied in a simplified load case

Authors' response to review

Please note that the comments from both reviewers have been arranged by section of the paper for a better overview. The corresponding changes made to the manuscript is marked with red.

No.	Reviewer	Comment	Authors response
General			
C1	2	The paper is generally well written, but there are a number of spelling and grammatical errors that need to be corrected. Some sentences are incomplete or read badly. Please proofread carefully and improve the language where it is needed.	Implemented - the manuscript has been reviewed thoroughly; spelling and grammar checked again and language improved.
1. Introduction			
C2	1	Referencing is good (although some corrections in the introductory section are necessary)	Implemented - all references in section 2 have been cross-checked and some updated/corrected.
2. Joint models for metocean parameters			
C3	1	In general, I think it is nice with a thorough overview of joint models as presented in Section 2. However, some parts of this seems a bit biased. For example, in the description of the conditional extremes model (section 2.2) the presentation does not seem to be very objective and all of the references seem to come from the same group of researchers that strongly advocate this model. • Did you do your own assessment og try out this method by yourself. Clearly, this method also has some drawbacks that are not sufficiently elaborated. • Moreover, section 2 could include some summary/concluding remarks arguing for the choice of models used in this study – i.e. the conditional modelling approach. Why did you choose this over all the others?	Implemented - this has been elaborated on in the text. • This has been commented in the text. • Section 2 is intended to give a general overview of the different approaches to joint modelling, advocated by their users. A more extensive argument for the background for the choice of models used in this study is included in section 4. Application of the other models to the same data set and comparison would be very useful and necessary before the best way to model waves and currents in the northern North Sea could be concluded, but this will be subject to further work.
C4	2	Section 2.2: The authors reference a number of articles from Lancaster University and Shell. Some of these articles address "conditional extremes" in the sense intended in this paper also. However, other articles address conditioning with respect to covariates (such as direction and season) which is not the sense intended in this paper (although this might still be important for realistic joint characterisation). I think the authors should make this clear, and revise 2.2 in this light.	Implemented - the section has been reviewed and rewritten; the references only considering one parameter conditioned on covariates has been removed.
4. Joint probability distribution of waves and currents			
C5	1	Section 4.1: You show that the selected marginal model fit the Hs-data quite well, but do not show any of the candidate models.	Implemented.

		• It would be useful to include similar figures for all candidate models that have been tried. Is the selected one significantly better than the others? Why was this chosen? • You could also report on one or more Goodness-of-fit statistics here to argue for your choice of model. • You also state that deviations from this model is "most likely within the statistical uncertainty bounds". It would be useful to quantify these uncertainty bounds to check if this is indeed true. • Finally, you state that with a threshold of 8 m there are 223 episodes, but on the next page you say 240. Which is correct? And is the annual occurrence rate correct? If not, the rest of the manuscript needs to be updated accordingly.	• All the tested marginal models have been given in figures and commented a bit further in the text. • The Kolmogorov-Smirnov test has been performed, but did not add much information. However, this is commented in the text. • Sentence removed. • The correct number is 240 and not 223. Fortunately, this is only a typo and the correct number of episodes has been used to estimate the annual occurrence rate.
C6	1	Section 4.2: • Again, it would be nice to have evidence that the selected model is indeed the best one. Could report GoF-statistics and figures for all candidate models to show that the one selected gives the best fit. • How did you estimate the parameters of the conditional distribution? Did you fit a model within each class in Fig. 4 or did you simply estimate the a- and b-parameters? By least squares/method of moments/ML? If so, what does the densities in Fig. 4 represent? This could be explained in more detail to make it more clear what exactly you do here.	Implemented. • To include figures with the other candidate models would require a bunch of extra figures, which are not considered to be very relevant for the work of this paper. There will always be some engineering judgement involved and as stated in the text - both the lognormal and Weibull 3-parameter distributions provided reasonable fits and could have been selected as conditional models, but the lognormal distribution was selected because of how the parameters varied through the Hs-classes. • The requested details have been included in section 4.2
C7	2	The authors do not consider wave direction and current direction as covariates in their model. Would the authors like to discuss to what this may be a limitation of the work? Are covariate effects important? Could diagnostic tests be made to show that covariate effects are not important in the current work?	Implemented - a brief discussion/comments regarding this is included in section 4.
C8	2	The conditional log-normal distribution for current speed has parameters which are themselves functions of Hs. The forms of the relationship between log-normal parameters and H_S are assumed linear; the corresponding intercept and slope parameter estimates are estimated. Near the conditional mean current, this is less to be a problem I guess, at least in terms of bias. To what extent is this problematic when extrapolating to very large conditional currents? Is there bias (and increased uncertainty) in the tails of conditional current distributions? Might this be important for design?	Implemented - this is commented at the end of section 4.2
C9	2	To what extent could the uncertainties in marginal model forms and parameter estimation be incorporated within the estimation of return values? I guess the Monte Carlo simulation could accommodate these sources of uncertainty quite easily? What effect might this have on return value estimates in terms of bias and uncertainty?	Implemented - this is briefly discussed at the end of section 4.1
5. Case study			
C10	1	Section 5.1: • In (9) it is (3), not (2) that is inverted. r_3h is not used anywhere –	Implemented. • Corrected.

		should be changed to r_Th. • I guess hmh means “most probable maximum”? You write “most probable value of H_mpm”. It is a bit unclear exactly what you mean here, so this should be rewritten to make the presentation clearer. • Also you could explicitly state that the two different statisics are used to give to different load assessments. • Moreover, Fig 5(II) does not suggest that it is appropriate to use a constant for sigma. Moreover, if you use constant values, then the distribution will not be conditional on Hs so you are actually just using a marginal distribution for Tp. Why is this OK? I think this part could be better explained and argued for why you don’t need any dependence of Hs in the conditional distribution of Tp.	• Rewritten. • Rewritten. • Commented and clarified in text - 95% confidence intervals have been included in the figure and just based on these the suggested simplification seems appropriate.
C11	1	Table 1: • Cs_ALS has the same value for 5%, MP, and 95% levels (64). Is this correct or a spelling mistake? Surely, there should be a spread in these values, so please check. • Include denomination in the table (e.g. “m” for Hs, etc…)	Implemented • This part has been rewritten/removed - according to comment C12 and also because introducing the Cs_ALS just creates unnecessary confusion and is not very relevant either since the simulations of Hs and Cs are completely independent. However, this was actually correct. According to the NORSOK N-003 recommendation, the Cs_{ALS} is the extreme current speed with an annual probability of 10^{-1}. Thus, the Cs_{ALS} could be set equal to Cs_{ULS}, but since two simulations of *Cs* has been performed (both for a 100 and 10 000 years period), it will be most correct to estimate Cs_{ALS} from the 10 000 years sample. For a longer sample of 10 000 years there will be less spread in the values corresponding to an annual probability of exceedance 10^{-1}, see figure below.  • Included in table.
C12	1	I wonder if you introduce a bias in the calculations of the NORSOK-loads. According to how I read this method in the paper, one should combine 10-	Implemented - the questions raised by the reviewer has been clarified and updates made accordingly through the entire Section 5. The reviewer

		2/10-4 levels of Hs with 10-1 levels of Cs. I guess the point here is that Hs is the governing parameter and one does not regard the joint probability of occurrence. Hence, the 10-1 level for the current is from the marginal distribution of currents. In your direct approach, you consider the joint distribution and calculate a time series of loads from concurrent values of Hs and Cs. However, when you compare with the NORSOK-approach in your paper, do you use 10-1 levels of Cs as simulated from the conditional model? I.e. conditional on Hs peaks above 8 m? This may not be the same as the marginal 10-1 level of Cs. Will this introduce a bias (towards higher Cs values?) in the analysis? Or did you make sure that either the bias is negligible or that you established a marginal distribution of Cs which you used? This is not clear, and I guess makes the comparison with NORSOK not correct. Please check this.	interpretation of how the case study has been performed is completely correct: when estimating the loads according to the NORSOK-approach, the marginal distribution for Hs (established in section 4.1) is used and a marginal distribution for Cs (which was established, but not reported). This is reported in section 5.1. Figure 7 (V) has been updated, as there was a typo in the xtick-names (resulting in the marked percentiles in this figure and Table 1 not matching) and accordingly also the corresponding numbers in Table 1 and 2.
C13	1	Section 5.2: You state that the ULS load calculated according to NORSOK is slightly less than the ULS load simulated directly from time series of the loads. Where can I find this in tables 1 and 2?? From the tables, it appears that NORSOK-results are higher in this case.	Implemented - this is a correct observation - many thanks! There has been a typo in the last column of Table 2, where the numbers have been switched. Also for the wave and current data simulated for a period of 100 years, the results based on the NORSOK N-003 approach is slightly conservative - as stated in Table 1.
C14	1	Fig. 9: Did you mix up data and fitted distribution for the validation period in the legend?? The thick dotted line looks more like a fitted distribution than the thin line. Please check. This applies to both the red and the blue lines.	Implemented - as stated by the review this is wrong and has been corrected accordingly.
C15	1	At the end of section 5.2 you state that figure 9 (III) gives higher loads for NORA10 than for the validation period. It seems to be opposite. Please check and explain. It would also be useful to indicate return periods along with the gumble scale along the y-axes in these plots.	Implemented - this is a correct observation - many thanks! Also here there has been a typo in the text, i.e. Figure 9 (III) is correct. As stated in the text, since there are a different number of occurences in the validation period, the NORA10 period and in most of the 5 years partitions the annual levels of occurences will be varying for each data set. The authors thinks indication of this on the figure would be more confusing than enlightening for the reader.

HIGHLIGHTS

- A joint conditional model for significant wave height and current speed is proposed for a location in the northern North Sea
- Significant wave height and current speed are well modelled by a 2-parameter Weibull and log-normal distribution, respectively
- Joint wave and current data for longer periods can be obtained by Monte-Carlo simulations from proposed joint model
- Simplified sensitivity studies give a clear indication that the Norwegian design standard is not necessarily conservative

TITLE

Joint description of waves and currents applied in a simplified load case

AUTHORS INFORMATION

- Kjersti Bruserud (corresponding author)

Affiliations and addresses:

1. Statoil ASA, Forusbeen 50, NO-4035 Stavanger, Norway
2. Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Otto Nielsens vei 10, NO-7491 Trondheim, Norway

E-mail: kjbrus@statoil.com

Cell phone: +47 95 75 79 46

Phone: +47 51 99 00 00

Fax: +47 51 99 00 50

- Sverre Haver

Affiliation and addresses:

    1. Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Kjell Arholms gate 41, NO-4036 Stavanger, Norway
    2. Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Otto Nielsens vei 10, NO-7491 Trondheim, Norway

E-mail: sverre.k.haver@uis.no

- Dag Myrhaug

Affiliation and addresses:

    1. Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Otto Nielsens vei 10, NO- 7491 Trondheim, Norway

E-mail: dag.myrhaug@ntnu.no

ABSTRACT

In order to perform a more accurate analysis of marine structures, joint probability distributions of different metocean parameters have received an increasing interest during the last decade, facilitated by improved availability of reliable joint metocean data. The main objective of this article is twofold: first to establish a joint distribution of significant wave height and current speed and then to assess the possible conservatism in the Norwegian design standard by applying this joint distribution in a simplified load case. There seems to be no general consensus with regard to the approach of estimating the joint probability distributions of metocean parameters and thus, a general overview of recent studies exploring different joint models for metocean parameters is presented first. Based on NORA10 wave data and simulated current data, a joint model for significant wave height and current speed at one location in the northern North Sea is presented. Since episodes of wind-generated inertial oscillations are the governing current conditions at this location, a conditional joint model with current speed conditional on significant wave height is suggested. A peak-over-threshold approach is selected and the significant wave height is found to be very well modelled by a 2-parameter Weibull distribution for significant wave height exceeding 8 m, while a log-normal distribution describes the current speed well. This model is used to Monte-Carlo simulate joint significant wave heights and current speeds for periods corresponding to the ultimate and accidental limit states (ULS and ALS), i.e. 100 and 10 000 years. The possible conservatism in the Norwegian design standard is assessed by a simplified case study. The results give a clear indication that the Norwegian design standard in not necessarily conservative, neither at ULS nor ALS level.

KEY WORDS

Waves; Currents; Joint probability distribution; Northern North Sea; NORSOK N-003

1. INTRODUCTION

Knowledge of the extreme meteorological and oceanographic (metocean) conditions and loading is required both in design and operation of marine structures such as offshore oil- and gas-producing facilities, wind power plants and pipelines. Design codes stipulate that offshore structures should be designed to exceed specific levels of reliability. To define extreme metocean loading, extreme metocean design criteria, primarily wind, waves and currents, must be specified. Accurate estimates of environmental design conditions, based on measured and/or hindcast data are of fundamental importance to the reliability of offshore structures over time. Thus, reliable metocean design criteria are essential in both design and operation of marine structures.

In order to perform a more accurate analysis of marine structures, joint probability distributions of different metocean parameters have received an increasing interest during the last decade, facilitated by improved availability of reliable joint metocean data. However, there still seems to be no general consensus with regard to the approach of estimating the joint probability distributions of metocean parameters and several different approaches are put forward. Jonathan and Ewans [1] gave a good theoretical overview of multivariate modelling of extreme ocean environments and guidelines for validity, but pointed out that "unfortunately there is as yet no unifying approach, and the literature is rather confusing". Ewans and Jonathan [2] concluded that specification of joint design criteria has often been somewhat ad hoc, based on experience and intuition and thus fairly arbitrary combinations of independently estimated extreme values. Vanem [3] demonstrated that there were large variabilities and thus large uncertainties in the estimated joint models due to different modelling choices, even for the same data set, and concluded that multivariate modelling of metocean conditions remains a challenge, even in the bivariate case.

For the Norwegian continental shelf (NCS), the design standard NORSOK N-003 [4] define the characteristic metocean loads and load effects in terms of their annual probability of exceedance, q. The requirements for ultimate and accidental limit state (ULS, ALS) for metocean actions on an offshore structure are $q \leq 10^{-2}$ and $q \leq 10^{-4}$, respectively. These requirements refer to the resulting metocean load obtained by accounting for simultaneous occurrence of metocean parameters such as wind, waves and currents. These parameters are not fully correlated and in order to utilize this for design, simultaneous data of high quality covering several years are required.

In lack of sufficient simultaneous metocean data, a combination of metocean parameters assumed to be conservative is recommended [4], but the degree of conservatism is not very well known. To utilize in design of offshore structures that the occurrence of metocean parameters is not fully correlated, the latest edition of NORSOK N-003 recommends at least three years of simultaneous wind, wave and current data. For Norwegian waters, high-quality measured and hindcast wind and wave data covering several decades are available. For currents, measured data is considered state-of-the art, but current measurements are rarely performed for more than one year. No available current hindcast for NCS is considered to have sufficient quality to base design criteria on. Thus, the availability of current data will be the limiting factor for estimation of joint distributions of wind, waves and currents.

Motivated by the need for high-quality current data of long enough duration for estimation of joint environmental conditions, extensive current measurements have been done at five locations in the northern North Sea [5]. The metocean measurement programme was initiated early 2011 and completed late 2015, i.e. a total duration of about 4.5 years. Simultaneous waves and current profiles were measured. Challenges related to the quality of measured current data have been reported and it is suggested that the accuracy of measured current data might not be as good as the user expects [6]. A new current hindcast has also been developed [7]. Comparison of available measured data in the northern North Sea and the new current hindcast showed a good correspondence. However, the quality of this current hindcast is not as good as the quality of available wind and wave hindcast for NCS and must be used with caution. Nevertheless, this hindcast constitute a very promising starting point for further development of an even better current hindcast for the northern North Sea. In summary, neither the measured nor the hindcast current data for the northern North Sea succeeded completely in providing the appropriate current data needed to establish joint distributions of metocean parameters in the northern North Sea. Considering the quality of measured current data, rather than to measure current simultaneously with wind and waves for a long period, it could prove to be more appropriate and prosperous to develop high-quality hindcast current data covering several years, validated with shorter periods of current measurements, to obtain adequate current data for estimation of joint environmental conditions.

The measured current data showed that currents from wind-generated inertial oscillations dominate the current conditions in the some parts of the northern North Sea, specifically in the area 59° to 60°N , 2° to 3°E. Following this, a simple model for wind-generated inertial oscillations has been applied to simulate current data of a long duration. Tuned with appropriate site-specific parameters for the northern North Sea and validated against available measured current data, this simple model generated current data of good enough quality.

The main objective of this paper is to establish a joint distribution for waves and currents based on simultaneous hindcast wave data and simulated current data. This joint description will be used to assess the possible conservatism in the N-003 requirements for a selected load case. A simplified parametric load model for quasi-static loads on a jacket, generated from waves and currents, is assumed. The ULS and ALS loads are then estimated based on the N-003 requirements for combination of metocean parameter and the metocean data simulated from the joint distribution of waves and current.

This article is outlined as follows: First, a general literature overview of recent advances in joint modelling of metocean parameters is given. Next, the available wave and current data in the northern North Sea are briefly described, before the joint probability distribution of waves and currents are presented. Then, the possible conservatism in N-003 requirement is assessed for a selected, simplified case study. At last, a summary is made.

2. JOINT MODELS FOR METOCEAN PARAMETERS

There is no unifying approach to joint modelling of metocean parameters. Several different approaches are put forward in the literature and strongly advocated by their users. Comparisons of the different approaches based on specific case studies are barely available and this makes it difficult to "benchmark" the different approaches. Each group of researchers seems to have their clear preferred approach and reason for this.

A general overview of recent studies exploring different joint statistical models to model offshore environmental conditions are given below. For simplicity, bivariate statistical models are often represented rather than the multivariate generalisations, but these are easily extended beyond two dimensions to multivariate models.

2.1. Conditional models

Joint distributions for different pairs of environmental parameters based on a marginal distribution of the primary parameter and a conditional distribution for the associated parameter are frequently used and also adopted in design codes. The two main advantages of the joint conditional model are (1) that the model is based directly on available data and thus known physics can be implemented in the modelling and (2) that application of the model is quite straightforward. However, selection of model to fit to available data and extrapolation of this are highly empirical and based on experience and engineering judgement.

Joint distributions of significant wave height and wave period, both zero up-crossing and spectral peak period, are extensively studied and numerous approaches are available in the literature. The joint environmental model proposed by Haver [8], Haver and Nyhus [9] based on a marginal hybrid lognormal-Weibull distribution of significant wave height and a conditional lognormal distribution of spectral peak period, is widely accepted and used. Later, this joint description of significant wave height and spectral peak period was extended to include wind speed, storm surge and current speed modelled with a normal distribution [10]. Based on a comparison of four different joint distribution functions for significant wave height and zero-up crossing period of measured wave data from three locations at the NCS, Mathisen and Bitner-Gregersen [11] recommended a similar conditional model for evaluation of extreme structural response to waves. Another conditional model considering significant wave height, mean zero-upcrossing period and wind speed off the southern coast of Norway was proposed by Belberova and Myrhaug [12]. Moan, Gao [13] utilised the joint probability density function for waves developed by Haver [8] when estimating the variability in the distribution of wave-induced response resulting from the variability in wave conditions. The conditional modelling approach for wind, waves and currents was extended to include directionality of the same parameters by Bitner-Gregersen [14]. Bitner-Gregersen and Guedes Soares [15] also used Haver's joint environmental model to estimate extreme wave steepness from different global numerical and measured wave databases. Joint models for both total, swell and wind sea significant wave height and spectral peak period were further investigated and uncertainties discussed by Bitner-Gregersen [16].

Conditional models for joint distributions for other pairs of metocean parameters such as wind, waves and currents have also been investigated. There are few available studies of the joint probability of waves and currents, probably due to the lack of simultaneous wave and current data and the complicated wave-current interaction mechanisms. However, both Gordon, Dahl [17] and Heideman, Hagen [18] investigated the relationship of extreme waves and currents based on simultaneous measurements at Tromsøflaket and established very simplified joint distributions of waves and currents used in load calculations and design for offshore structures. Wen and Banon [19] developed a probabilistic methodology that lead to joint probability distributions of hurricane induced wind, waves and currents at a generic site in the Gulf of Mexico. Based on a simple bi-variate Weibull distribution, Prior-Jones and Beiboer [20] estimated joint design criteria for current speed and waves and highlighted the need to develop sound design practices for application of the joint environmental probability factors. Joint probabilistic models have been proposed for waves and current [21] and wind and waves [22] based on simultaneous measurements from the northern North Sea. This model has later been applied off the northwestern coast of Germany [23]. Another approach to probabilistic modelling of metocean parameters, based on a general kernel density model, was introduced by Athanassoulis and Belibassakis [24] and found to perform satisfactory for a case study of wave parameters measured off the Portuguese coast. Ferreira and Guedes Soares [25] suggested that for some applications, a non-parametric model based on kernel density estimates for significant wave height and mean zero-upcrossing period can be used instead of parametric models. Liu, Song [26] presented a joint probability design method based on a stochastic simulation technique (Importance Sampling Procedure Using Design Point) to determine the combined environmental design criteria of wave, current and wind and found this approach to give less conservative and more reasonable design criteria when applied for different marine structures.

Based on the first-order reliability method (FORM), the inverse-FORM (IFORM) methodology for joint distribution of sea state parameters, often referred to as IFORM contours, was introduced [27]. Applications and refinements of the environmental contour lines for significant wave height and peak period were given in Haver and Kleiven [28] and Haver and Winterstein [29]. Fouques, Myrhaug [30] proposed a general methodology aimed at modelling seasonal joint distributions for different metocean parameters from their correlation structure and marginal distributions, which was applied to establish different contour lines for a simple example of significant wave height and mean zero-crossing period. Nerzic, Frelin [31] derived joint extremes of waves, wind and current and also IFORM contours offshore Angola. So-called "polygonal contours" was developed as a practical method to implement a multivariate environmental contour approach and applied to a case-study of at FPSO in West Africa [32]. De Masi, Mattioli [33] estimated contours for cyclone wind speed paired with associated parameters such as waves, currents and surge. Extended data analysis for better representation of the measured wave data prior to the application of the IFORM for generating environmental contours, has recently been proposed [34] and argued to result in more realistic representation of the environmental contours.

2.2. Heffernan and Tawn conditional extremes model

Many of the conditional models of multivariate extreme value analysis assume a particular form of extremal dependence between the environmental variables. Models are also restricted to joint regions in which all variables are extreme at the same time, but regions where only a subset of variables is extreme can be equally important for design of offshore structures. The semi-parametric conditional extremes model introduced by Heffernan and Tawn [35] avoids these particular restrictions. The main refinement of this approach compared with other conditional models is that the functional forms for marginal fitting and conditional modelling is motivated by asymptotic arguments. The model is considered to be easily implemented with the following main steps: (1) marginal modelling of all parameters with a generalized-Pareto distribution, (2) transformation of the data into a Gumbel scale using the probability integral transform, (3) estimation of the conditional extremes model and (4) simulation of long return period to estimate joint extremes. The two main advantages of the conditional extremes model are (1) that all different types of extremal dependence between metocean variables can be modelled and (2) that the model is relatively easy to implement, also for high dimensions, i.e. many different metocean parameters.

The conditional extremes model has been applied for several studies of joint parameters, including but not limited to, environmental parameters. This conditional extremes model for estimation of joint distributions of metocean parameters is strongly advocated by its users and a series of studies where this model has been adopted and applied has been published.

Jonathan, Flynn [36] adapted the conditional model to joint modelling of wave climate parameters, i.e. significant wave height and peak period, and demonstrated that the model performed reasonable in application to both measured and hindcast data taken from four different world-wide locations. In Jonathan, Ewans [37] modelling of the vertical profile of current conditions based on the conditional extreme models was done and applied on measured current data from north western Australia. Ewans and Jonathan [2] reviewed contemporary methods for estimation of joint extreme environmental variables related to design and reliability of offshore structures. The conditional extremes model was strongly recommended for joint modelling of metocean parameters.

The conditional extremes model has been extended for non-stationary environmental conditions, i.e. incorporation of directional, spatial and temporal covariate effects such as directionality and seasonality. The first study of covariate effects in the framework of the conditional model was given by Jonathan, Ewans [38], where an extended conditional model incorporating covariate effects was described and illustrated for joint modelling of storm peak significant wave height and peak period with storm direction as covariate at a northern North Sea location. Towe, Eastoe [39] estimated the extremal dependence between storm peak significant wave height and wind speed, also with storm direction as covariate, for several locations in the northern North Sea and suggested that covariate effects are important when environmental design criteria are developed. Ewans and Jonathan [40] summarized the developments in methods for estimating extreme metocean design criteria. Several examples of application for both marginal and conditional methods incorporating covariates were provided and incorporation of covariate effects was concluded to improve model fits in general and reduce modelling uncertainty. The latest development of the conditional extremes model with covariates includes joint estimation of multivariate extremes with multi-dimensional covariates [41], applied in the northern North Sea for current speed sconditional on significant wave height with wave and current direction as two covariates. The estimated omni-directional joint extreme value for current speeds was found to be significantly reduced compared to the corresponding marginal value.

2.3. Bivariate models

Bivariate modelling with parametric probability distributions for different combinations of environmental parameters has been performed based on a wide range of different parametric bivariate distributions. This approach is valid when an appropriate distribution is chosen. However, it can be difficult to decide the goodness of the different parametric distributions and toselect the most appropriate distribution. In addition, the parametric bivariate models are typically fitted to the body of available data and not focused on the extremes which are the main interest for design of offshore structures.

Athanassoulis, Skarsoulis [42] proposed a Plackett bivariate model to represent the joint probability distribution of significant wave height and mean zero-upcrossing period. This model has later been used to model the joint distribution of significant wave height and storm duration [43]. Morton and Bowers [44] provided a detailed examination of employing a multivariate point process model in extreme value analysis and established a bivariate distribution of wind and waves in the northern North Sea. Zachary, Feld [45] reviewed and simplified the multivariate theory developed by Coles and Tawn [46], Coles and Tawn [47], before it was applied to wind and wave data collected in the northern North Sea, with short-term variability and seasonality included.

Less conservative design loads compared to the traditional approach have motivated an extensive investigation of bivariate modelling of environmental parameters for Chinese waters such as the East and South China Sea and Bohai Sea. For calculation of the joint probability of extreme wave height and wind speed during a storm or typhoon process Duan, Zhou [48] applied a simplified Logistic model, Liu, Wen [49] a Poisson-Gumbel Mixed Compound distribution, Dong, Xu [50] a Poisson Bivariate Gumbel Logistic distribution, Dong, Liu [51] a Poisson Bivariate Log-Normal distribution, Dong, Ning [52] and Dong [53] a Poisson Bivariate Logistic distribution and Dong, Liu [54] a Bi-variable Pearson-

III distribution. Dong, Wang [55] proposed and applied a Trivariate Nested Logistic Distribution to estimate joint probability of wind speed, significant wave height and current velocity in the Bohai Sea. These approaches were suggested to be more objective and reasonable for estimation of environmental extreme values for design.

A different approach to bivariate modelling of environmental parameters is to use maximum entropy distributions. Liu, Dong [56] proposed a Bivariate Maximum Entropy distribution of wave height and wind speed in the Bohai Sea, which was further investigated by Dong, Fan [57]. This methodology was also considered for significant wave height and corresponding peak period at one location in the North Atlantic and compared to other bivariate approaches [58].

The main conclusion of all these studies of different bivariate and maximum entropy distributions for Chinese waters was that all these models were more capable of describing the environmental loads from wind, waves and currents on marine structures, than the marginal distributions. However, the goodness of the different applied models relative to each other has not been considered and such a discussion would be useful.

2.4. Copula

The use of copula techniques for modelling of different combinations of environmental parameters has become increasingly popular in recent years and a number of studies have proposed bivariate models based on different copula techniques. In practice, a multivariate distribution function is constructed by combining the marginal distributions of the metocean parameters with a specific dependence structure, modelled by the selected copula. However, selection of the most appropriate copula to model the dependency structure between the variables can prove difficult. The suitability of the copula approach for metocean parameters has not been examined extensively, but it has been indicated that standard copulas fail to model complicated dependence structure between wave parameters such as significant wave height and zero up-crossing period [3].

A general approach to the construction of a multivariate model, tested against data of sea storms parameters such as significant wave height, storm duration, storm direction and storm interarrival time, was given in De Michele, Salvadori [59]. For the joint probability of significant wave and wind speed, Norouzi and Nikolaidis [60] used a copula and demonstrated the proposed approach for an offshore wind park in Lake Erie (US). For the Bohai Bay (China), both Tao, Dong [61] and Yang and Zhang [62] constructed joint distributions of significant wave height and wind speed based on different bivariate copulas. Xu, Chen [63] further investigated the use copula for these two parameters. Salvadori, Tomasicchio [64] reviewed previous work of the copula techniques, outlined a practical guideline for multivariate analysis for environmental parameters based on copula and applied it on a case-study of wave data measured off the northern coast off Sardinia (Mediterranean Sea). Li, van Gelder [65] tested two copula functions to model joint distributions of significant wave height, peak period, storm duration and surge along the Dutch coast. Dong and Li [66] constructed bi- and trivariate distributions of wave height, wind velocity and current velocity with the Plackett copula. Environmental contours based on multivariate distributions constructed from bivariate copulas were discussed and applied for significant wave height, peak period and wind velocity in the Gulf of Mexico by Montes-Iturrizaga and Heredia-Zavoni [67]. Vanem [3] made an extensive comparison of several joint models of significant wave height and zero-crossing wave period based on parametric families of copulas to conditional and bivariate parametric models. The results suggested that that joint models constructed from copula compared well with Haver's conditional model, but challenges and limitations with the copula technique were emphasised.

Joint probability distributions of metocean variables based on the Nataf distribution have been developed in some studies. The Nataf distribution can be considered a special case of the copula technique, since the correlation between the random variables in the Nataf model corresponds to that defined by a Gaussian copula. Ditlevsen [68] formulated a Nataf model for the joint distribution of significant wave height, zero upcrossing period and wind velocity pressure. Sagrilo, de Lima [69] utilised 2 years of simultaneous environmental data measured offshore Brazil to create joint probability models of 10 wave, wind and current parameters, based on the Nataf transformation. Silva-González, Heredia-Zavoni [70] developed environmental contours of variables having a joint distribution defined by the Nataf transformation.

3. DATA

Brief descriptions of the different metocean data used to establish the joint distributions of waves and currents and for the case study are provided in this section. More detailed descriptions of the measured metocean data are provided in Bruserud and Haver [5], [6], the North Sea Reanalysis Archive (NORA10) hindcast data in Bruserud and Haver [7] and the simulated current data in Bruserud, Haver [71].

3.1. Metocean measurements

The metocean measurement programme at five locations in the northern North Sea, see Figure 1 (I), was initiated early 2011, with the main phase starting in May 2011. At Location 3, The measurements were ended late 2013 at Location 3, but continued until October 2015 at the four other locations. In general, the data coverage at each location was good, ranging from around 80 % to 95 %.

The measurements were performed with the same generic mooring design at all locations, which consisted of one surface mooring and one seabed mooring. The surface mooring included a Wavescan buoy measuring surface waves and a downward-looking acoustic current profiler (Nortek 600 kHz Aquadopp, AQD) measuring near-surface current speed and direction. The seabed mooring was designed to measure current speed and direction throughout the entire water column and near seabed by two near-bottom upward-looking acoustic current profilers (Teledyne RD Instruments 150 kHz Quartermaster ADCP, QM ADCP and Teledyne RD Instrument 1200 kHz Workhorse ADCP, WH ADCP). A schematic outline of the mooring configuration and the instrument types is given in Figure 1 (II). All current meters were set to record samples at 10-minutes intervals. However, the sampling methods and ensemble intervals were different for the different types of current profilers.

Although extensive quality control of the measured current data has been done, the accuracy of the measured current data was found to be less than the specified accuracies of the instruments. Extensive efforts have been made to resolve these quality issues, but have so far not succeeded [6]. As a preliminary, preemptive measure until more insight is acquired, measured current data from the surface and down to 40 m water depth are not considered to have sufficient quality to be included in further analysis. In addition, a 70-minutes running mean is applied to the measured current speeds at all other water depths. This is considered to yield an adequate data quality of measured current data to base reliable analysis on.

3.2. Norwegian Reanalysis Archive (NORA10)

The NORA10 hindcast is a regional hindcast for the northeast Atlantic, including the North Sea, the Norwegian Sea and the Barents Sea, developed by the Norwegian Meteorological Institute [72, 73]. The hindcast is a dynamical downscaling of the global reanalysis, European Reanalysis project (ERA-40) [74, 75].

The ERA-40 dataset covers the period from September 1957 to August 2002, which is the original period of NORA10. However, NORA10 is extended continuously based on downscaling of operational analyses by the European Centre for Medium-Range Weather Forecasts (ECMWF) and updated with a delay of approximately 2 months. The routines for these operational analyses have been changed several times since 2002 and this might inflict on the data homogeneity of NORA10 after year 2002. The period of NORA10 data available for this study is September 1957 through December 2015. The data is assumed to be homogeneous during the entire period, but the data quality has probably improved somewhat with time as more measured meteorological data have become available during the last decades. In addition, the significant wave heights for the northern North Sea from around 2010 up to date have been found to be overestimated somewhat for the largest observed storms.

The model output of hindcast data is 3 hours. In principle, this model output gives the conditions at that exact point of time, i.e. not any sort of 3 hours averaging. In practice, due to the temporal resolution of the wind field forcings and the spatial resolution of the wave model, the hindcast data is assumed to represent a 1-hour mean value. This is supported by the fact that NORA10 significant wave height is found to fit best to hourly measurements of significant wave height (personal communication with Magnar Reistad at the Norwegian Meteorological Institute).

3.3. Simulated currents

The measured current from the northern North Sea showed that wind-generated inertial oscillations dominate the current conditions in parts of the northern North Sea [5]. Based on this, the simple model for wind-generated inertial oscillations proposed by Pollard and Millard [76] has been adapted for the northern North Sea [71]. The main input for this model is time-series of the wind speed. The model has been validated and compared against measured current data at one location (Location 4) and found to reproduce the maximum current speed in each episode of wind-generated inertial oscillations with reasonable accuracy. The comparison is further improved when a small general background current is added to the simulated maximum current speed.

This validated model has been applied with NORA10 wind data during the entire NORA10 period, i.e. September 1957 to December 2015, to simulate the episodes of wind-generated inertial oscillations for a long period of more than 58 years. Based on well-defined criteria on the wind speed and direction triggering wind-generated inertial oscillations, 2800 episodes of wind-generated inertial oscillations were identified, i.e an annual occurrence rate of 48.1. Since this study focuses on extreme metocean criteria, the maximum simulated current speed in each episode will be selected for further analysis. Thus, a data set of 2800 simulated maximum current speed values will be available.

According to the NORA10 hindcast data, the simulations were done with an input time step of 3 hours (NORA10 time step), but the simulated wind-generated inertial currents can be extracted for any required point of time during the simulations. Since current measurements at the NCS are normally performed with a 10-minutes averaging interval, the simulated wind-generated inertial currents were extracted for every 10-minutes interval. Correspondingly, the duration of the maximum simulated current speed in each episode is considered to be 10-minutes.

4. JOINT PROBABILITY DISTRIBUTION OF WAVES AND CURRENTS

Simultaneous wave and current data describing the governing wave-current climate at Location 4 in the northern North Sea can be obtained by combining the simulated current data set consisting of 2800 episodes of wind-generated inertial oscillations with the corresponding NORA10 hindcast wave data.

As stressed earlier in this paper, there still seems to be no general consensus with regard to the approach of estimating joint probability distributions of metocean parameters and several different approaches are advocated strongly by different groups. At Location 4 in the northern North Sea, wind-generated inertial oscillations have been documented to generate the largest current speeds [5, 71]. This implies that the governing current conditions are directly linked to the wind conditions. The wave climate is dominated by wind-sea, which again means that the wave conditions are closely related to the wind conditions and may be taken as an “extension” of the wind conditions. Considering these physical conditions, a conditional joint model with currents conditional waves is considered appropriate for joint modelling of waves and currents at Location 4 in the northern North Sea. However, application and comparison of other approaches to joint modelling based on the same wave and current data must be done before any conclusion regarding the most appropriate joint modelling of waves and currents can be made. To apply the conditional model of waves and currents would be a first step towards a joint model. Application and comparison of other models would be subject to further work.

The long-term variation of waves and currents is assumed to be properly described by a conditional joint probability density distribution of significant wave height, *Hs*, and current speed, *Cs*, given by

$$f_{HsCs}(hs,cs) = f_{Hs}(hs) f_{Cs|Hs}(cs\,|\,hs) \quad (1)$$

where $f_{Hs}(hs)$ is the marginal density distribution for *Hs* and $f_{Cs|Hs}(cs|hs)$ is the conditional density distribution for *Cs* given *Hs*. For simplicity, wave and current directions are not considered as covariates in the model in this novel work with joint modelling of waves and currents in the northern North Sea. This is expected to introduce some conservatism. However, wave and current directions may be implemented as covariates in the model in future work.

The scatter and q-q plots of maximum *Hs* and *Cs* the episodes of wind-generated inertial oscillations are shown in Figure 2. The scatter plot shows that the highest *Cs*, in the range 60 to 100 cm/s, correspond to a range of both intermediate and large *Hs* of around 8 m to nearly 14 m. The *Cs* associated with the highest waves, i.e. waves exceeding 10 m, are in the interval around 30 cm/s to 85 cm/s. A wide spread is indeed evident, but it is obvious that large *Cs* can occur simultaneous with high *Hs*.

4.1. Marginal distribution of significant wave height (*Hs*)

Several different approaches to model the marginal distribution of *Hs* have been considered such as 2- and 3-parameter Weibull distributions fitted to all the 2800 episodes of *Hs* and 2- and 3-parameter Weibull distributions fitted to the episodes of *Hs* exceeding a wide range of thresholds from 3 m to 13 m. The distributions were all fitted by the method of moments.

Figure 3 (I) shows the empirical and fitted 2- and 3-parameter Weibull distribution to all *Hs* data. Both distributions follow the data closely up to about 9.5 m. Then the 2-parameter Weibull distribution starts to deviate from the data, while the 3-parameter Weibull distribution first starts to deviate from the data at about 11 m. Figure 3 (II) shows the empirical and fitted 2- and 3-parameter Weibull distribution to all the episodes of *Hs* exceeding a threshold of 8 m, which was found to be most appropriate. In total 240 episodes with a maximum *Hs* exceeding 8 m were identified. In general, the both distributions follow the empirical data closely. For *Hs* exceeding about 11.5 m, some slight deviations between the data and the fitted distribution are evident, with the 2-parameter Weibull distribution slightly more conservative than the 3-parameter Weibull distribution.

All distributions expect the 2-parameter Weibull distribution fitted to all *Hs* data seem like adequate fits to the data. The Kolmogorov-Smirnov test confirms that the *Hs* data could have all these three distributions, but rejects the 2-parameter Weibull distribution fitted to all *Hs* data. Both Weibull distributions fitted to *Hs* exceeding 8 m follow the tails of the empirical distribution more closely than the 3-parameter Weibull distribution fitted to all *Hs* data. Thus, both these are considered to give a better fit, with the 2-parameter Weibull distribution slightly more conservative than the 3-parameter Weibull distribution. This is the reason why the 2-parameter Weibull distribution fitted to the episodes of *Hs* exceeding 8 m was selected over the 3-parameter Weibull distribution to model the marginal distribution of *Hs*

$$f_{Hs}(hs) = \frac{\gamma}{\beta}\left(\frac{hs - hs_0}{\beta}\right)^{\gamma - 1} exp\left[-\left(\frac{hs - hs_0}{\beta}\right)^{\gamma}\right] \tag{2}$$

$$F_{Hs}(hs) = 1 - exp\left[-\left(\frac{hs - hs_0}{\beta}\right)^{\gamma}\right] \tag{3}$$

where hs_0 equal to 8 m is the selected threshold for *Hs*, β is the scale parameter and γ is the shape parameter, estimated to 1.095 and 1.15, respectively.

The engineering judgement involved when considering what is the most appropriate distribution to model a specific data set and how to estimate the parameters of the selected model, is a source of uncertainty, i.e. epistemic uncertainty. The natural randomness of the environmental conditions is another source of uncertainty, i.e. aleatory uncertainty. Performing a Monte-Carlo simulation from the selected, fitted distribution could accommodate some of these uncertainties. The uncertainties could be communicated by providing a range of distribution parameters and accordingly a range of estimated extreme values, rather than just single numbers.

4.2. Conditional distribution of current speed given significant wave height (*Cs*|*Hs*)

To model the conditional distribution of *Cs* given *Hs*, 2- and 3-parameter Weibull distributions were applied and also a log-normal distribution. Both the 3-parameter Weibull distribution and log-normal distribution provided an appropriate fit to the *Cs* data for given *Hs*. Since the parameters of the log-normal distribution showed a more smooth variation, this distribution was chosen to model the conditional distribution of *Cs*|*Hs*

$$f_{Cs|Hs}(cs|hs) = \frac{1}{\sqrt{2\pi}\sigma cs} \cdot exp\left[-\frac{1}{2}\left(\frac{ln(cs) - \mu}{\sigma}\right)^2\right] \tag{4}$$

$$F_{Cs|Hs}(cs|hs) = \frac{1}{2} erfc\left[-\left(\frac{ln(cs) - \mu}{\sqrt{2}\sigma}\right)\right] \tag{5}$$

where μ is the mean value and σ the standard deviation of ln($cs|hs$) and erfc the complementary error function.

To estimate the conditional log-normal distribution for *Cs*|*Hs*, the current data was first divided into different classes according to corresponding *Hs* value and the mean value, μ, and standard deviation, σ, for each *Hs* class was estimated by the method of moments. The density and cumulative conditional distributions of *Cs* for given classes of *Hs* are shown in Figure 4. The corresponding log-normal parameters, expected value μ and standard deviation σ of $\ln(Cs|Hs)$ with 95 % confidence intervals, are given in Figure 5 (I). For the three first *Hs* classes, i.e. *Hs* between 8 and 11 m, both the fitted density and cumulative distributions correspond well to the data. In the two classes of highest *Hs*, i.e. *Hs* between 11 and 13 m, there are few observations, but the fitted distributions still gives a reasonable representation of the *Cs* data. This is also reflected in the estimated log-normal parameters for the different *Hs* classes where the uncertainty in the estimated parameters for the three first *Hs* classes is very low, but larger for the two highest *Hs* classes. This indicates an increased uncertainty in the tails of the conditional current distributions.

The estimated log-normal parameters for *Cs*, μ and σ, are seen to increase slightly with higher *Hs* and can be expressed by the following simple linear fits

$$\mu = a_1 + a_2 hs \tag{6}$$

$$\sigma = b_1 + b_2 hs \tag{7}$$

where a_1 and a_2 are constants estimated to 2.4 and 0.13, respectively, b_1 and b_2 are constants estimated to 0.15 and 0.0087, respectively, and *hs* is the significant wave height. It is chosen not to introduce any upper bounds in this model. This may be problematic and result in too large and non-physical values of current speed when extrapolating to very large conditional current speeds.

5. CASE STUDY

For a jacket, the governing load process is the hydrodynamic load caused by waves and currents. A simple parametric model for overturning moment of a jacket, which neglects the effect of dynamics, was developed by Heideman [77]. The model can be used to estimate a generic, static load, L, on a jacket and is given as

$$L = K_1 (H + K_2 Cs)^{K_3} \tag{8}$$

where H is individual wave height [m], Cs is depth integrated current speed [m/s] and K_1, K_2 and K_3 are empirical constants. For a drag dominated jacket platform in about 100 to 200 m water depth, the following parameters are expected to give reasonable quasi-static loads: K_1 set to 0.03, K_2 set to 5.5 and K_3 set to 2.2 [78]. It is obvious from the empirical constants that the waves will be most important for the loads.

The load model given in Equation (8) is used to estimate the ULS and ALS loads on a jacket by the following two approaches

1. NORSOK **N-003** approach (denoted N-003): In lack of more detailed and verified joint models of actions, the Norwegian design standard NORSOK N-003 Edition 3 [4] recommends an approach to combination of actions assumed to be conservative (see Section 10.3, Table 7). To obtain the ULS and ALS loads, waves with annual probability of exceedance 10^{-2} and 10^{-4}, respectively, shall be combined with currents of annual probability of exceedance 10^{-1}. This means that H of annual probability of exceedance 10^{-2} and 10^{-4} should be combined with Cs annual probability of exceedance 10^{-1} in Equation (8). For this approach, marginal distributions of waves and currents must be established.
2. A **direct** approach (denoted direct): The load model can also be applied to obtain a time series of the load by combining simultaneous data of H and Cs into Equation (8). Then the ULS and ALS loads can be estimated directly from this time series of the load. For this approach, a joint distribution of waves and current must be established.

5.1. Simulation of wave and current data

The established joint model of waves and currents can be used to Monte-Carlo simulate samples of wave data required for both load estimation approaches (marginal wave data) and also the current data required for the direct approach. For the N-003 approach, independent current data is necessary and can be obtained by Monte-Carlo simulation from a marginal distribution fitted to the simulated current data.

The Monte-Carlo simulation of wave and current data for both approaches of load estimation is summarized in the following steps:

1) Simulate *Hs*

When Equation (3) is inverted, *Hs* will be given as

$$Hs = hs_0 + \beta\left[-ln\left(1 - r_{Hs}\right)\right]^{1/\gamma} \tag{9}$$

where r_{Hs} is a random number between 0 and 1 representing a possible realisation of $F_{Hs}(hs)$.

2) Estimate *H*

H can be estimated from the inverted Forristall' s distribution for individual waves [79]. To assess the effect of short-term variability in *H* on the load assessment, two different approaches to estimate *H* have been pursued

(I) Including short-term variability in *H*

$$H_{mpm} = Hs\left[-\frac{1}{2.263}\left(ln\left[1 - r_{H_{mpm}}(h)^{\frac{1}{n}}\right]\right)\right]^{\frac{1}{2.126}} \tag{10}$$

where r_{Hmpm} is set to 0.37 which gives the most probable maximum of *H* denoted H_{mpm}

(II) Excluding short-term variability in *H*

$$H_{Th} = Hs\left[-\frac{1}{2.263}\left(ln\left[1 - r_{H_{Th}}(h)^{\frac{1}{n}}\right]\right)\right]^{\frac{1}{2.126}} \tag{11}$$

where r_{HTh} is a random number between 0 and 1 which gives one possible realisation of *H* during *T* hours denoted H_{Th}

In both cases, n is the expected number of individual waves during T hours, i.e. $T\cdot 3600/Tz$, where Tz is the zero up-crossing period. Here, T is 3 hours and Tz is approximated by $0.77Tp$. Correspondingly, the number of waves will be approximated by $10800/0.77Tp$ and Tp given the simulated Hs will be prerequisite of simulating H_{mpm}/H_{3h}.

Tp is assumed to be independent of Cs and the conditional distribution of $Tp|Hs$ is modelled by a log-normal distribution, as proposed by Haver [8]

$$Tp = exp\left[\left(-\sqrt{2}\sigma erfc^{-1}\left(2r_{Tp|Hs}\right)\right) + \mu\right] \tag{12}$$

where $r_{Tp|Hs}$ is a random number between 0 and 1 representing a possible realisation of $F_{Tp|Hs}(tp|hs)$ and μ and σ are the fitted parameters of the log-normal distribution. The estimated log-normal parameters of $\ln(Tp|Hs)$ are given in Figure 5 (II), with 95 % confidence intervals. For μ, the uncertainty increases with larger Hs. For σ^2, the uncertainty is large for all classes of Hs. For simplicity, μ is set to 2.2 and σ^2 set to 0.05. It could be argued more correct to estimate Tp by more sophisticated expressions for the parameters of the log-normal distribution. Considering (1) the scarcity of data point to fit expressions of μ and σ to, (2) the spread and uncertainty in these data points and (3) how this distribution will be further used, such simplicity is the expression for μ and σ^2 is considered appropriate.

3) Simulate *Cs*

For the N-003 approach, a marginal distribution for Cs has been established by fitting a Weibull 3-parameter distribution to the maximum Cs during all the 2800 episodes of wind-generated inertial oscillations, as proposed by Bruserud and Haver [80], Bruserud and Haver [81]. Cs will be given as

$$Cs = \alpha + \beta\left[-ln\left(1 - r_{Cs}\right)\right]^{1/\gamma} \tag{13}$$

where r_{Cs} is a random number between 0 and 1 representing a possible realisation of $F_{Cs}(cs)$ and α, β and γ are parameters of the fitted Weibull 3-parameter distribution, estimated to be 18.60, 7.60 and 0.983, respectively.

For the direct approach, the simulated Hs is inserted in Equation (6) and (7) to estimate the parameters μ and σ of the log-normal distribution for Cs, before Cs will be given by the inverted Equation (5)

$$Cs = exp\left[\left(-\sqrt{2}\sigma\, erfc^{-1}\left(2r_{Cs|Hs}\right)\right)+\mu\right] \qquad (14)$$

where $r_{Cs|Hs}$ is a random number between 0 and 1 representing a possible realisation of $r_{Cs|Hs}(cs|hs)$.

4) Repeat the steps 1 to 3 in order to obtain a sample of desired duration

As the number of episodes of wind-generated inertial oscillations with *Hs* exceeding 8 m during 58.25 years is 240, the annual rate of occurrence is 4.12. Thus, a sample of simulated *Hs, Tp and* H_{mpm}/H_{3h} representing a 100 years period will consist of 412 sets of simulated values and 10 000 years period of 41 202. For the direct approach, this will also apply for *Cs*. However, for the N-003 approach, the annual rate of occurrence is 48.07 (i.e. 2800 episodes/58.25 years) and correspondingly the 100 year and 10000 year samples will consist of 4807 and 480 687 values, respectively.

5) Repeat the steps 1 to 4 in order to capture the natural variability

To capture the natural variability, this Monte-Carlo simulations have been repeated 100 times, i.e. 100 samples of *Hs, Tp, Cs* and H_{mpm}/H_{3h} have been simulated. Please note that the first values corresponding to 100 years of the 10 000 years samples could have been used to represent the 100 years samples. However, it is chosen to simulate the 100 years' samples separately.

The scatter and qq-plots of the samples representing 100 years of joint wave and current data are shown in Figure 6, together with the scatter and qq-plots of the NORA10 hindcast wave data and the corresponding simulated current data. Although the scatter and qq-plots are based on different data sources and cover different ranges, a smooth variation is seen in the overlap and transition of the two different data sets. This is interpreted as a good indication of that both the joint distribution of waves and currents and simulated data from the joint distribution are well representing the original wave and current data.

5.2. Load estimation

N-003 approach. For ULS and ALS load estimation according to NORSOK N-003, H_{mpm}/H_{3h} of annual probability of exceedance 10^{-2} and 10^{-4} are required, respectively, together with *Cs* of annual probability of exceedance 10^{-1}. For H_{mpm}/H_{3h}, the largest estimated value in each sample of 100 and 10 000 years will be a possible representation of H_{mpm}/H_{3h} with annual probability of 10^{-2} and 10^{-4}. For

Cs, the values corresponding to the level of annual probability 10^{-1} of the samples of 100 and 10 000 years will be a possible representation of Cs with annual probability 10^{-1}. In order to emphasize the variation between the different 100 samples, the 5 % percentile, most probable value and 95 % percentiles of H_{mpm}/H_{3h} and Cs at the respective levels of annual probability of exceedance are extracted and summarized in Table 1. To be consistent with the two separate simulations of 100 and 10 000 years' periods of data, the possible representation of Cs with annual probability of 10^{-1} should be extracted from both these data sets. The most probable value of Cs are the same and only Cs from the 100 years sample is included.

The simulated samples of Hs, Tp, H_{mpm}/H_{3h} and Cs corresponding to 100 years' period are shown in Figure 7. The 5 % percentile, most probable value and 95 % percentiles of H_{mpm}, H_{3h} and Cs at the respective levels of annual probability are marked with red squares. The samples for the 10 000 years' period have very similar forms and are not shown. Even though physical considerations are not included in the Monte Carlo-simulations, all the samples of simulated Hs, Tp, Cs and H_{mpm}/H_{3h} shown in Figure 7 are seen to give realistic values, which could very well be observed in the nature. For all parameters shown in Figure 7, there is little spread between the 100 different samples in the lower parts of the empirical distributions and as expected the spread increases gradually in the higher parts. For Cs, larger spread is observed than for Hs, Tp and H_{mpm}/H_{3h}. When comparing the two different ways of estimating the individual wave height, H_{mpm} to H_{3h}, the spread in the samples is similar, but the simulated H_{3h} seem to be slightly more conservative than the H_{mpm}.

By applying the most probable values for H_{mpm}/H_{3h} and Cs (from Table 1) in Equation (8), the corresponding ULS and ALS load can be estimated according to N-003. The timing of waves and currents has not been investigated, so the ULS and ALS loads based 5 % and 95 % percentile values have not estimated since these will not necessarily occur at the same time. The estimated loads are given in Table 1, denoted N-003.

Directly approach. With the samples corresponding to periods of 100 and 10 000 years, each simulated set of H_{mpm}/H_{3h} and Cs can be combined directly into Equation (8) and thus 100 samples of the estimated load, L, during 100 and 10 000 years have been obtained. The 100 samples L corresponding to 100 and 10 000 years' periods are shown in Figure 8. A Weibull 3-parameter distribution has been fitted to each sample and the corresponding ULS load estimated for samples of 100 years' duration and ALS load for samples of 10 000 years' duration. The 5 % percentile, most probable value and 95 % percentiles of estimated ULS and ALS loads are summarized in Table 1.

Load comparison. When comparing the estimated ULS loads based on the N-003 approach and the direct approach, based on either H_{mpm} or H_{3h}, the values are for all practical purposes identical, with the ULS loads based on N-003 approach slightly larger than the direct approach. Estimated ULS loads based on H_{3h} are for both approaches somewhat larger than the corresponding loads based on H_{mpm}. At ALS level, no clear pattern is evident in the estimated ALS loads. For the ALS loads based on H_{mpm}, the N-003 approach yields slightly smaller ALS load than the direct approach. For the ALS loads based on H_{3h}, the ALS load directly from a time series of the load is slightly smaller than the N-003 approach.

5.3. Discussion

Previous case studies investigating the possible conservatism of the NORSOK N-003 requirement have been published based on the same methodology but with different joint wave and current data. Bruserud and Haver [80] utilised idealised measured current data from a deep water location in the Norwegian Sea combined with corresponding NORA hindcast wave data during nearly 4 years, while Bruserud and Haver [81] used measured wave and current data from the northern North Sea during 4.5 years. In Bruserud [82] the effect of different types of current data combined with measured and hindcast wave data in the northern North Sea during the measurement period of 4.5 years and the NORA10 period of 58.25 year were investigated. In these studies, the extreme values required to estimate and compare extreme loads were estimated from fitted distributions to the wave and current data. These three comparisons indicated a possible conservatism in the NORSOK N-003 requirement, though only a slight conservatism in some of the cases based on the full NORA10 period of 58.25 years.

The results presented here are not directly comparable to the previous published results since (1) the wave and current data are not the same regarding data type, duration and location, and (2) the extreme values required to estimate and compare extreme loads are estimated differently. In order to relate the results of this case study to previous work, the ULS load has been estimated based on the same wave and current data as the joint model was fitted to, i.e. NORA10 hindcast wave data and simulated current data, according to the two different approaches. The load estimation has been done for the validation period of the current simulations, i.e. 4.5 years of current measurements, and the NORA10 period, i.e. 58.25 years. Following this, the ULS load has been estimated from fitted distributions to the data. A comparison of the estimated extreme loads is given in Table 2. To ease comparison, the load has been normalized to the load estimated based on the NORSOK N-003 requirement for the full NORA10 period. For the validation period of 4.5 years, the ULS load estimated according to the NORSOK N-003 requirement is considerable larger than the ULS load estimated directly from a time series of the load. This indicates some conservatism in the NORSOK N-003 requirement. For the NORA10 period, the difference in estimated ULS loads is significantly diminished. Both these comparisons are found to agree with previous published results. For the full 100 years period with simulated data from the joint model for waves and currents, the ULS load estimated according to NORSOK N-003 is also slightly larger than the ULS load estimated directly from a time series of the load, consistent with results based on the NORA10 period. These results indicate that the NORSOK N-003 requirement is not necessarily conservative for ULS and also the importance of sufficient available data.

The comparison of estimated ULS loads for the validation period and the two longer periods differ substantially. Since the results from the validation and NORA10 periods are directly comparable because they are based on the same joint wave and current data and way of estimation of extreme values, an attempt to explain the differences is done considering the validation period against the NORA10 period. Since the wave data basis in NORA10 is Hs this parameter is considered rather than the estimated H. However, H is expected to vary in a qualitatively similar way. Comparison of the maximum Hs (Hs_{max}), maximum Cs (Cs_{max}) and the mean load (L) during each episode of wind-generated inertial oscillations for the validation and NORA10 periods are shown in Figure 9. To investigate how the validation period compares to other periods of similar duration, the full NORA10 period has also been partitioned into five year periods. Both the data, i.e. empirical distributions, and fitted distributions are shown.

In Figure 9 (I) Hs_{max} is shown. A clear variation and spread in both empirical and fitted distributions are evident for the different 5 year periods. The variation between the different periods increases with increasing Hs_{max}. In general, the validation period is found to comprise larger Hs_{max} data than most of the other 5 year periods. Correspondingly, the fitted distribution is also more conservative when compared to the other periods. As expected, the entire NORA10 period is placed in the midst among the

5 year periods and seen to differ from the validation period. Due to different number of occurences and duration of the compared data, the levels of annual probability of exceedance will vary as well for the 5 years and NORA10 periods. For the 5 years periods, the corresponding levels of annual probability of exceedance will be similar, but higher for the NORA10 period. Consequently, with the observed slope of the fitted distribution, the extreme Hs_{max} will be less for the NORA10 period than the validation period, which implies a similar variation for H. In the case study presented in this paper, waves will be most important for the estimated loads. This difference in Hs_{max} results in a significantly smaller ULS load for the NORA10 period than the validation period when estimated according to the NORSOK N-003 requirement. This is expected to explain most of the difference in the results for the validation and NORA10 period.

In Figure 9 (II) Cs_{max} is shown. There is a larger variation and spread in empirical and fitted distributions of Cs_{max} than for Hs_{max}, increasing with larger values of Cs_{max}. The validation period is among the more severe periods of Cs_{max}, but not very different from the NORA10 period. Thus, the current conditions are expected to have little effect on the difference in estimated ULS loads for the validation and NORA10 periods.

The corresponding comparison of L is given in Figure 9 (III). A similar variation as for Hs_{max} is seen between the different data. However, the slope of the fitted distributions is different, resulting in slightly larger extreme L for the validation period than the NORA10 period. This increase in extreme L also contribute to reduce the difference between the estimated ULS loads based on the two different approaches from the validation period to the NORA10 period.

6. SUMMARY

The main objective of the presented work has been to establish a joint distribution of waves and currents, for assessment of the possible conservatism in the Norwegian design standard, NORSOK N-003.

Based on simulated current data and NORA 10 wave data, a joint conditional probability distribution of current and waves has been established where the significant wave height *Hs* has been modelled by a 2-parameter Weibull distribution for *Hs* exceeding 8 m and the conditional current speed *Cs* given *Hs* has been modelled by a log-normal distribution. This joint model can be used to simulate joint wave and current data for periods of longer durations.

The possible conservatism in the NORSOK N-003 requirement for ULS and ALS load estimation has been investigated by a case study. A simplified model for a generic, static load on a jacket is assumed. Joint wave and current data corresponding to periods of 100 (ULS) and 10 000 (ALS) years have been simulated, both from marginal and the joint model. The ULS and ALS loads have been estimated both according to the NORSOK N-003 requirement and directly from a time series of the load. The individual wave height is estimated in two different ways. Comparison of the ULS and ALS loads based on the two different approaches gives a clear indication the NORSOK N-003 requirement is not necessarily conservative, neither at ULS nor at ALS level.

There will be uncertainties in the estimated ULS and ALS loads based on the NORSOK N-003 approach and directly on a time series of the load due to several simplifications in the different steps leading towards the estimated ULS and ALS loads. The Pollard-Millard model used to simulate the wind-generated currents, is a very simplified current model and the quality of measured current data used to validate this model has proved to be, at best, questionable. Uncertainties are also related to the statistical models fitted to model the long-term variation in *Hs*, *Cs* and *Tp*. The applied load model is also a very simplified model. Due to the much longer duration of simulated joint wave and current data for consideration of ALS loads than ULS loads, these results are likely to be more uncertain. It is necessary to determine whether these results hold when a more detailed approach to estimation of ALS loads are pursued. However, the comparison of the estimated ULS and ALS based on these two different approaches is still expected to give a clear indication that NORSOK N-003 requirements for ULS and

ALS for estimation of environmental actions are not particularly conservative, neither at ULS level nor at ALS level.

Due to several simplifications in the different steps leading to the estimated ULS and ALS loads, the results of the present study are intended to be illustrative. Before a more definitive conclusion regarding the conservatism of the NORSOK N-003 requirement may be made, it would be necessary to determine if the presented results hold when other approaches to joint modelling of waves and currents are applied, when a more sophisticated load model is applied and also when wind data is included in both the load model and joint conditional distribution. However, this will be subject to further work.

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TABLES

Table 1 The estimated ULS and ALS loads according to the two different approaches, with normalized loads given in parenthesis to ease comparison. The estimated extreme *H* and current speeds *Cs* which are used to estimated ULS and ALS loads according to NORSOK N-003 are also included.

Parameter	**Unit**	**Percentile**		
		5 %	**Most probable**	**95 %**
$H_{mpm,ULS}$	m	22.6	24.2	27.3
$H_{3h,ULS}$		24.3	26.0	30.2
$H_{mpm,ALS}$		29.5	31.0	36.6
$H_{3h,ALS}$		32.2	34.4	40.1
$Cs_{ULS\ and\ ALS}$	cm/s	63	67	72
$ULS_{N\text{-}003,\ Hmpm}$	N		45 (1.00)	
$ULS_{N\text{-}003,\ H3h}$			52 (1.16)	
$ULS_{directly,\ Hmpm}$		39 (0.87)	43 (0.96)	54 (1.20)
$ULS_{directly,\ H3h}$		43 (0.96)	49 (1.09)	62 (1.38)
$ALS_{N\text{-}003,\ Hmpm}$			73 (1.00)	
$ALS_{N\text{-}003,\ H3h}$			90 (1.23)	
$ALS_{directly,\ Hmpm}$		76 (1.04)	79 (1.08)	86 (1.18)
$ALS_{directly,\ H3h}$		82 (1.12)	86 (1.18)	96 (1.32)

Table 2 Estimated, normalized ULS loads according to the two different approaches for three different periods. The results for the 100 years of simulated data is based on the H_{3h}, since this is most comparable to the corresponding individual wave height for the two other periods.

Period	**Validation** 4.5 yrs	**NORA10** 58.25 yrs	**Simulated** 100 yrs
N-003	1.37	1.00	1.06
Directly	1.04	0.94	1.00

FIGURES

The figure captions are listed below:

Figure 1 (I) Metocean measurement locations and (II) generic mooring design at each location.

Figure 2 Scatter and qq-plot of Hs and Cs of NORA10 hindcast wave data and simulated current data.

Figure 3 Empirical and fitted distributions of Hs

Figure 4 Conditional distribution for $Cs|Hs$; log-normal (I) density and (II) cumulative distributions for different Hs classes.

Figure 5 Parameters for conditional distribution of (I) $Cs|Hs$ and (II) $Tp|Hs$.

Figure 6 Scatter and qq-plot of Hs and Cs of simulated wave and current data during 100 years from the established joint fitted model together with NORA10 hindcast wave data and simulated current data as shown in Figure 2.

Figure 7 Empirical distributions of the 100 Monte Carlo-simulated (I) *Hsmax*, (II) *Tp* (given *Hsmax*), (III) *Hmpm* , (IV) H3h and (V) Csmax corresponding to a period of 100 years. For $_{Hmpm}$ and Csmax the 5 %, most probable and 95 % percentiles of the largest values are marked with red squares.

Figure 8 Empirical (blue squares) and fitted (red lines) distributions of the 100 Monte Carlo simulated (I) ULS load based on *Hmpm* and (II) ULS load based on *H3h.* The black squares show all the Monte Carlo simulated samples combined.

Figure 9 Comparison of empirical (squares) and fitted (dotted) distributions of (I) *Hsmax,* (II) *Csmax* and (III) mean L in episodes of wind-generated inertial oscillations during the validation period (red), NORA10 period (black) and 5 year partitions of the NORA10 period (blue)

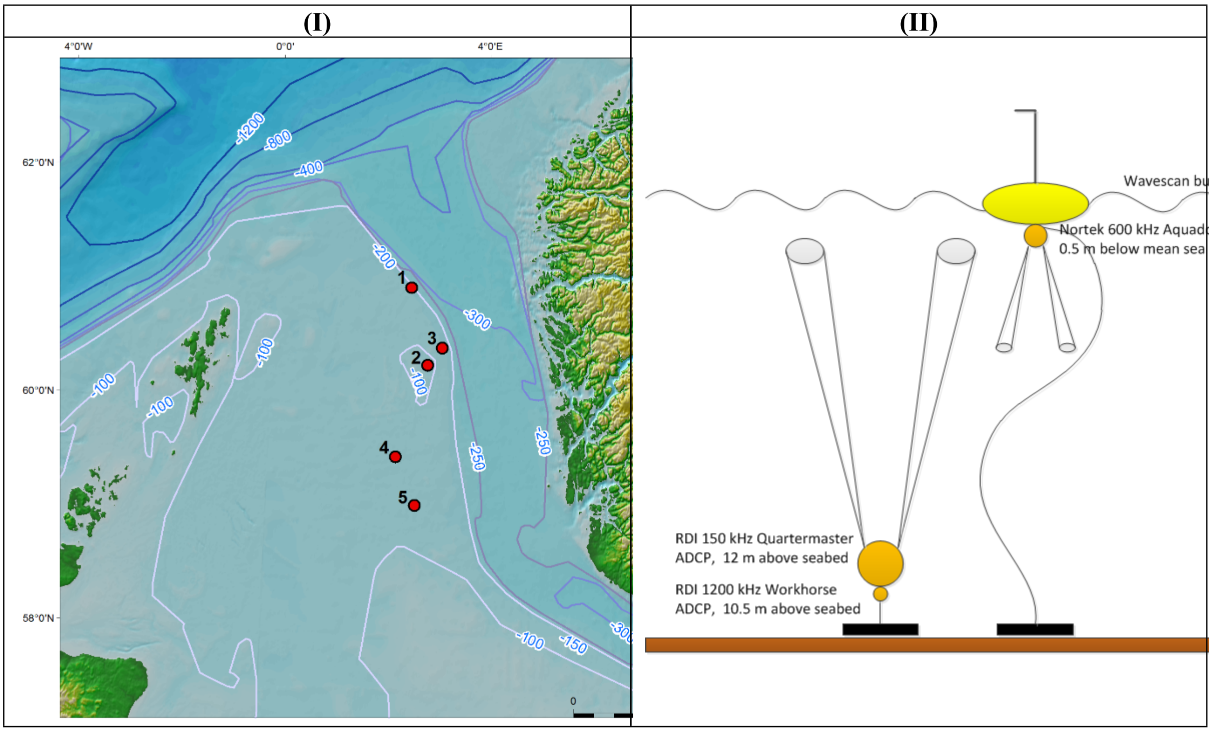


Figure 1 (I) Metocean measurement locations and (II) generic mooring design at each location.

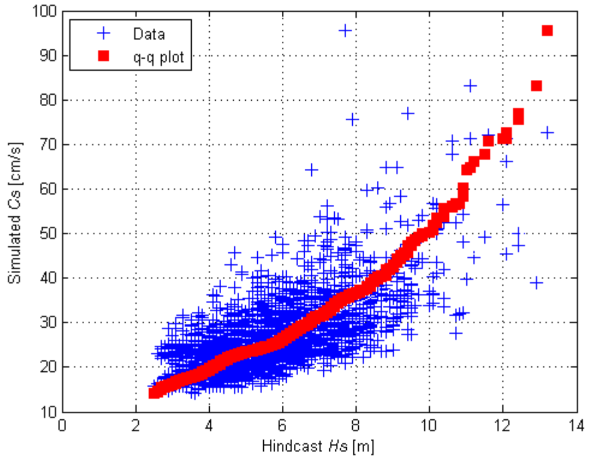


Figure 2 Scatter and qq-plot of *Hs* and *Cs* of NORA10 hindcast wave data and simulated current data.

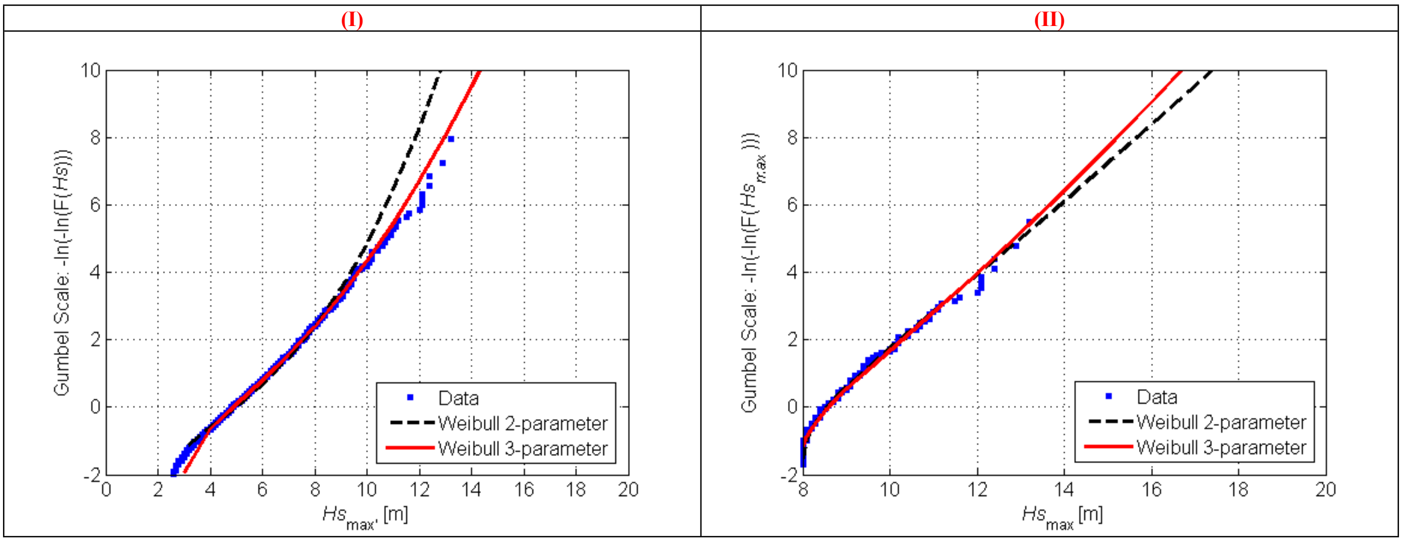
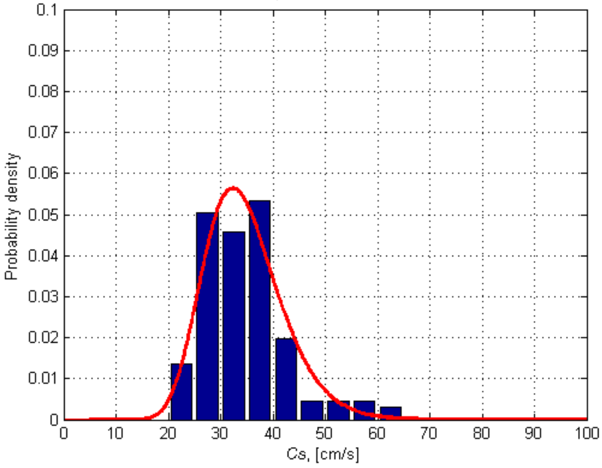
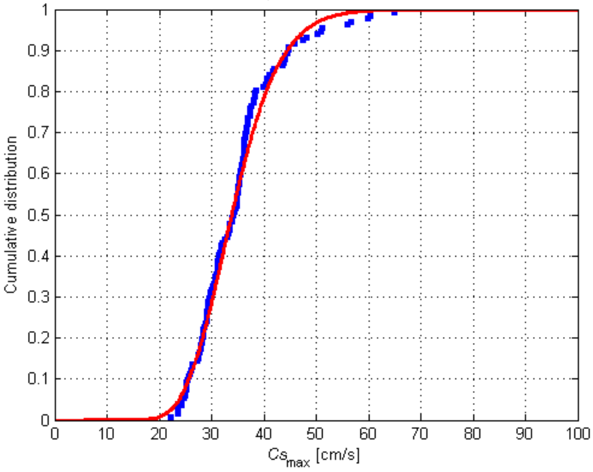
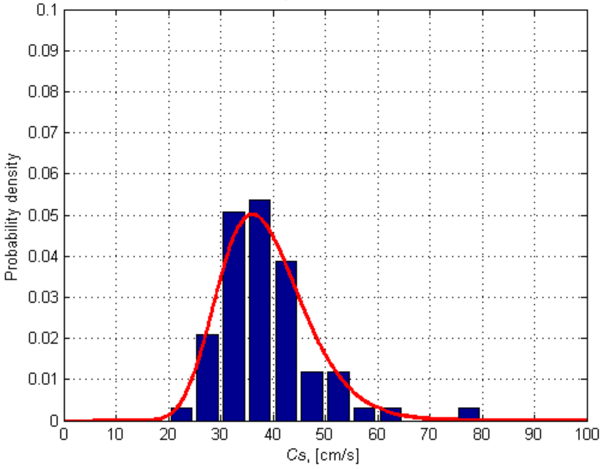
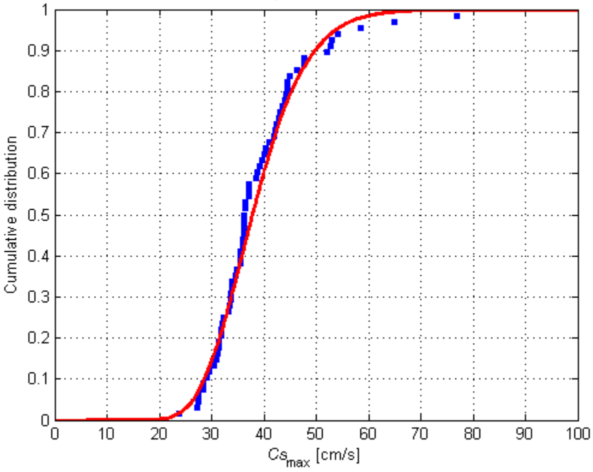
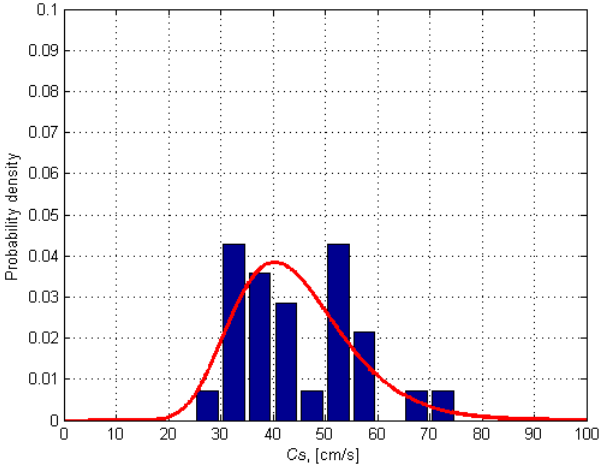
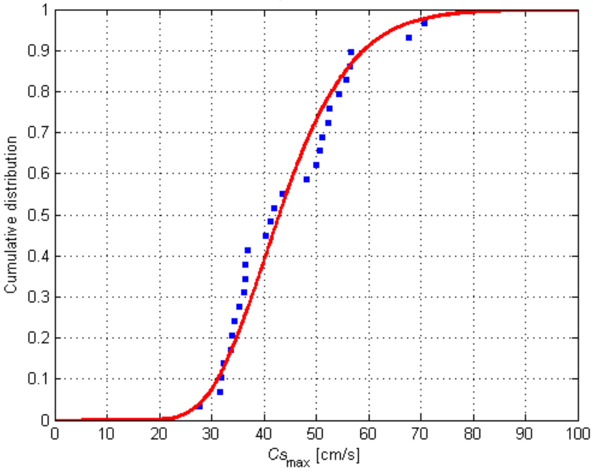
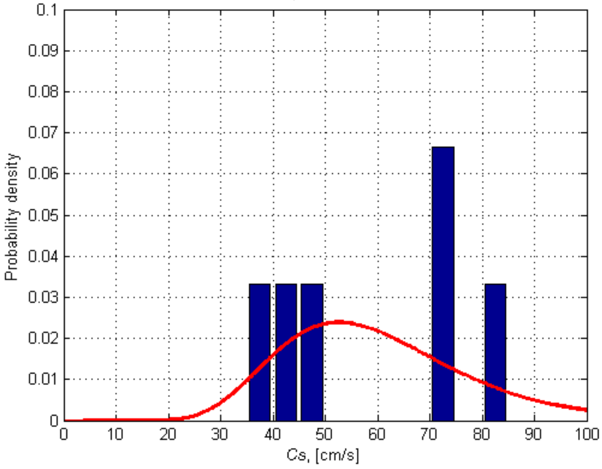
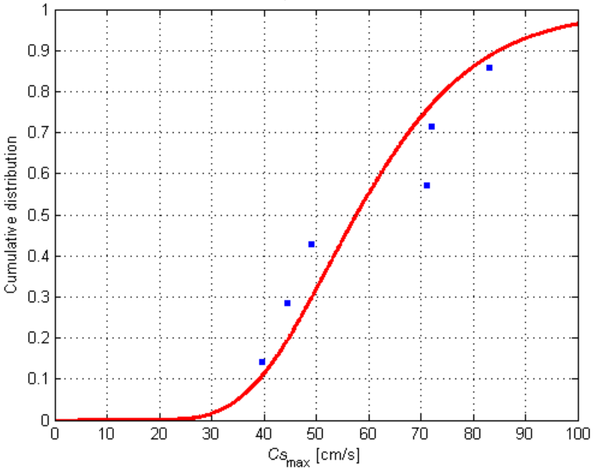


Figure 3 Empirical and fitted distributions of *Hs*, based on (I) all episodes of *Hs* and (II) the episodes of *Hs* exceeding 8 m.

(I)	(II)
 *Hs* - 8 to 9 m, number observations - 131	 *Hs* - 8 to 9 m, number observations - 131
 *Hs* - 9 to 10 m, number observations - 67	 *Hs* - 9 to 10 m, number observations - 67
 *Hs* - 10 to 11 m, number observations - 28	 *Hs* - 10 to 11 m, number observations - 28
 *Hs* - 11 to 12 m, number observations - 6	 *Hs* - 11 to 12 m, number observations - 6

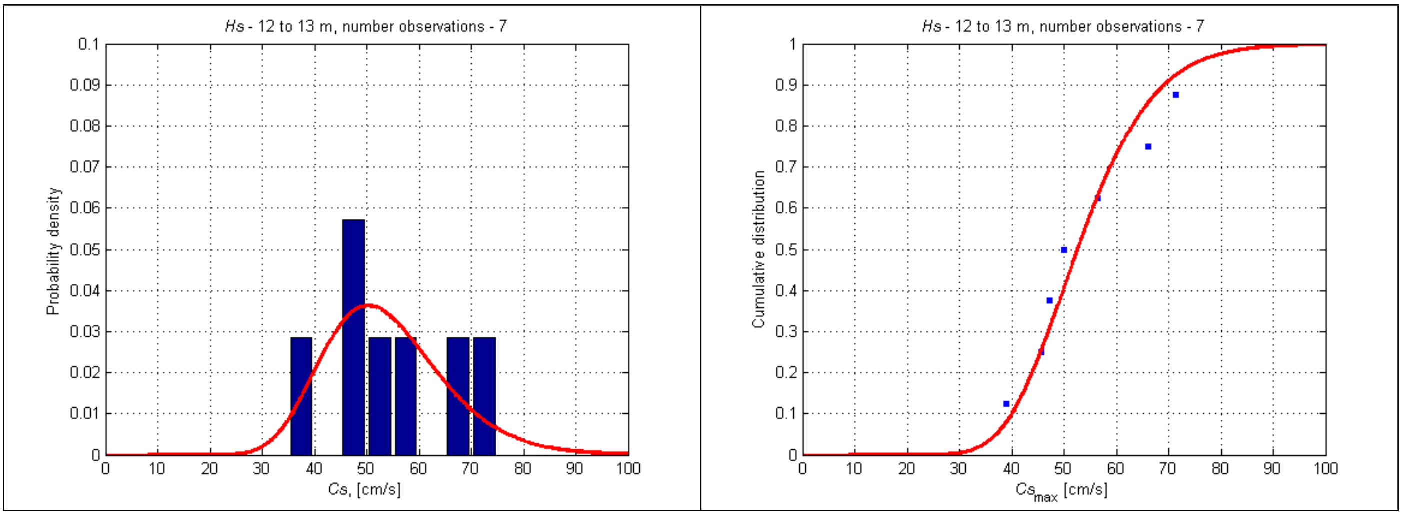


Figure 4 Conditional distribution for *Cs*|*Hs*; log-normal (I) density and (II) cumulative distributions for different *Hs* classes.

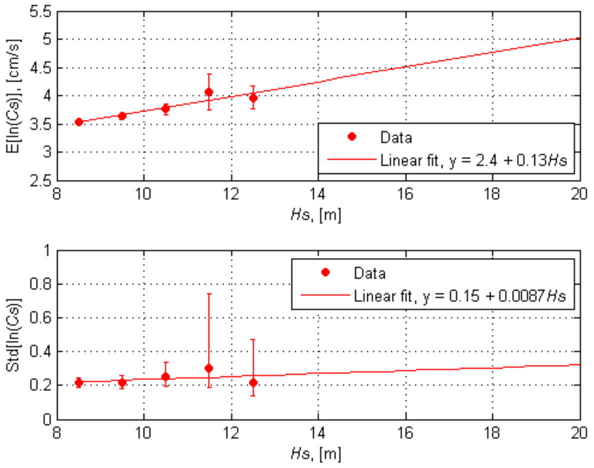
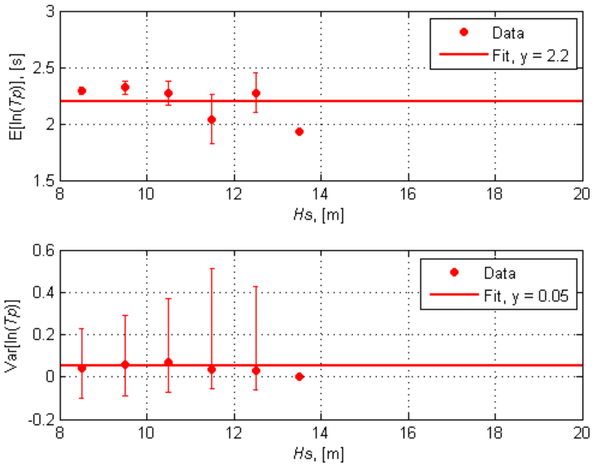
(I)	**(II)**
	

Figure 5 Parameters for conditional distribution of (I) $Cs|Hs$ and (II) $Tp|Hs$.

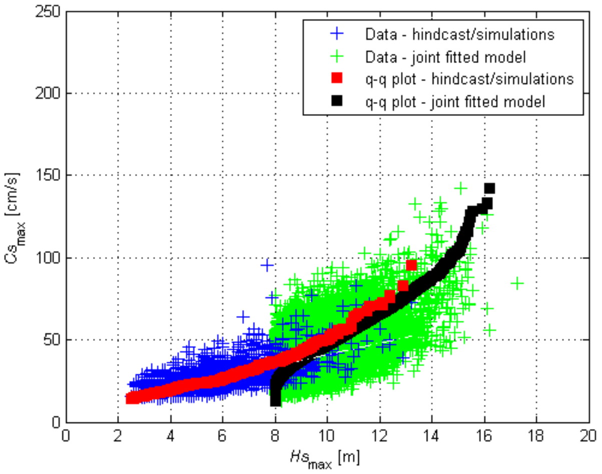


Figure 6 Scatter and qq-plot of *Hs* and *Cs* of simulated wave and current data during 100 years from the established joint fitted model together with NORA10 hindcast wave data and simulated current data as shown in Figure 2.

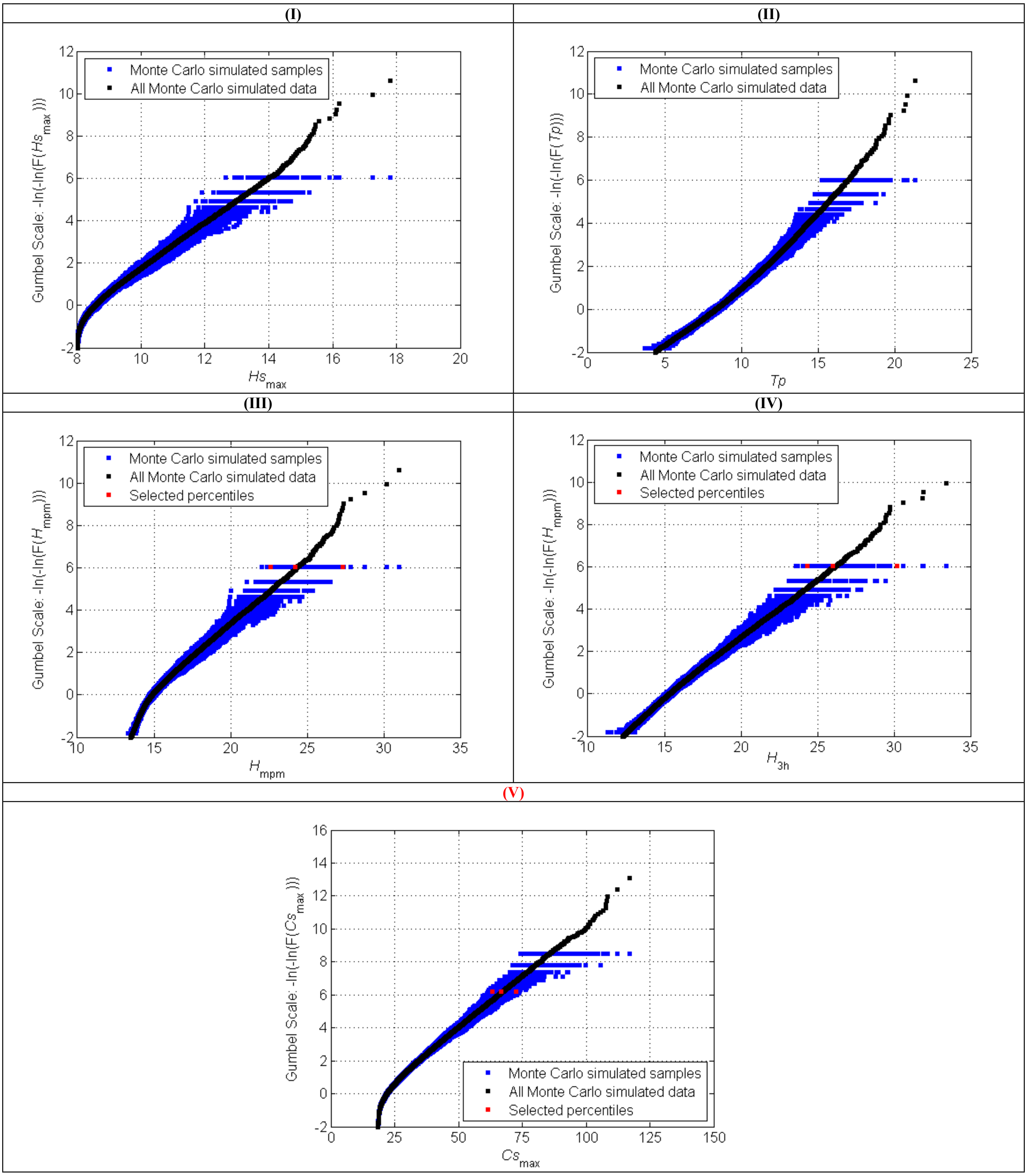


Figure 7 Empirical distributions of the 100 Monte Carlo-simulated (I) Hs_{max}, (II) Tp (given Hs_{max}), (III) H_{mpm} , (IV) H_{3h} and (V) Cs_{max} corresponding to a period of 100 years. For H_{mpm} and Cs_{max} the 5 %, most probable and 95 % percentiles of the largest values are marked with red squares.

(I)	(II)

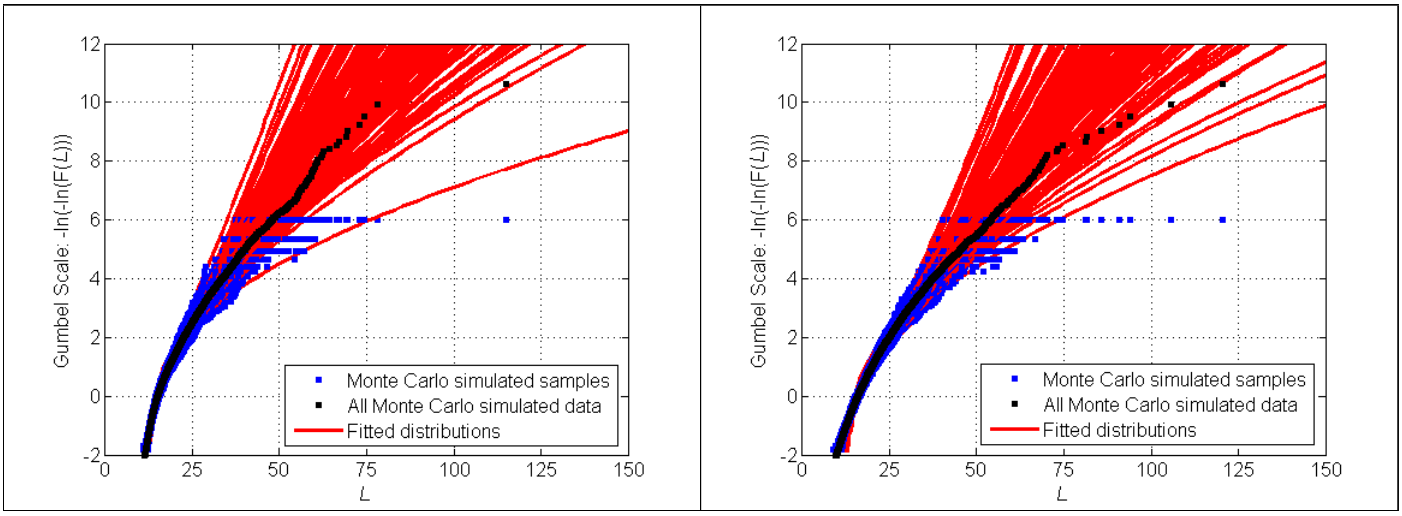


Figure 8 Empirical (blue squares) and fitted (red lines) distributions of the 100 Monte Carlo simulated (I) ULS load based on H_{mpm} and (II) ULS load based on H_{3h}. The black squares show all the Monte Carlo simulated samples combined.

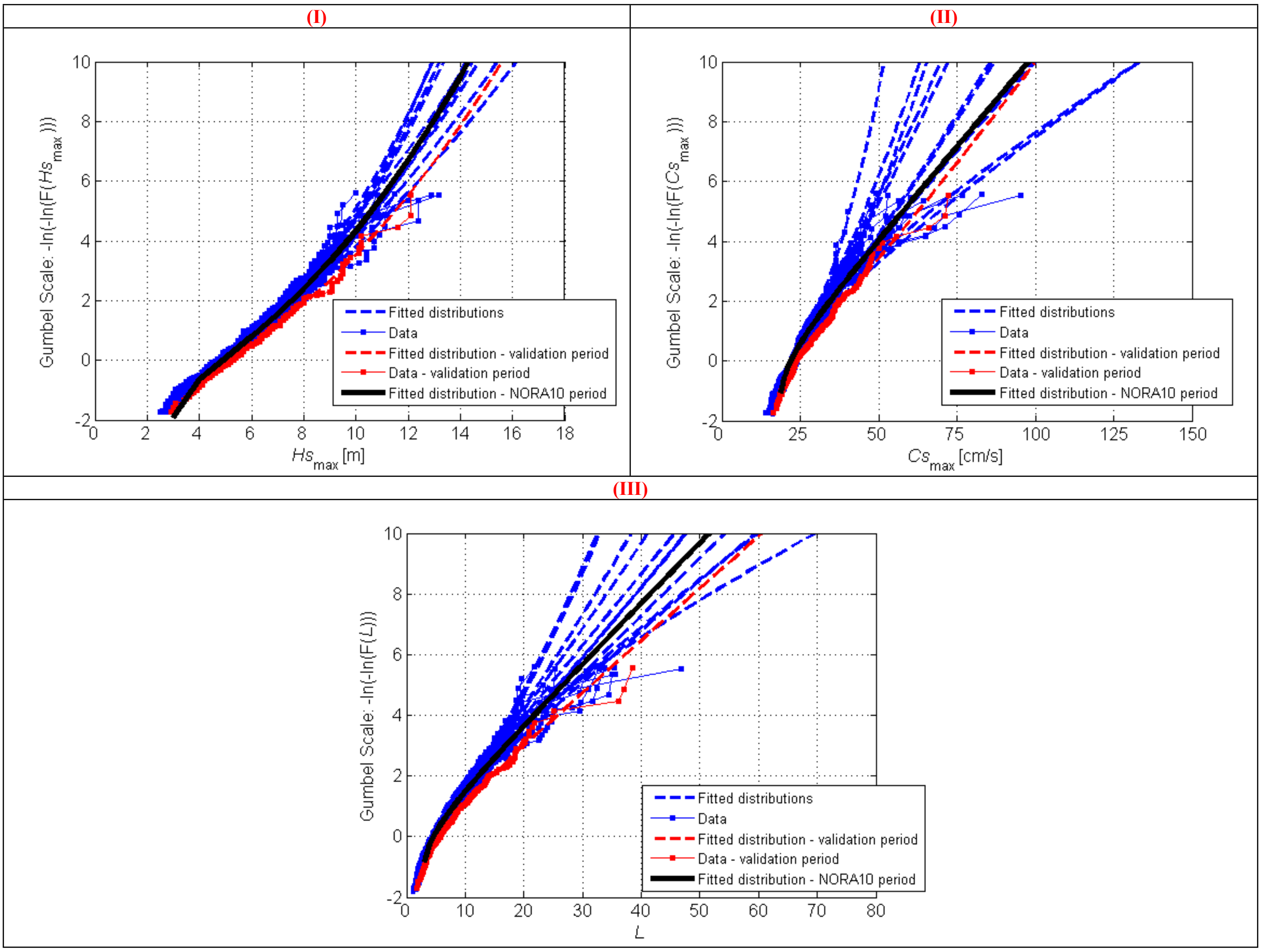
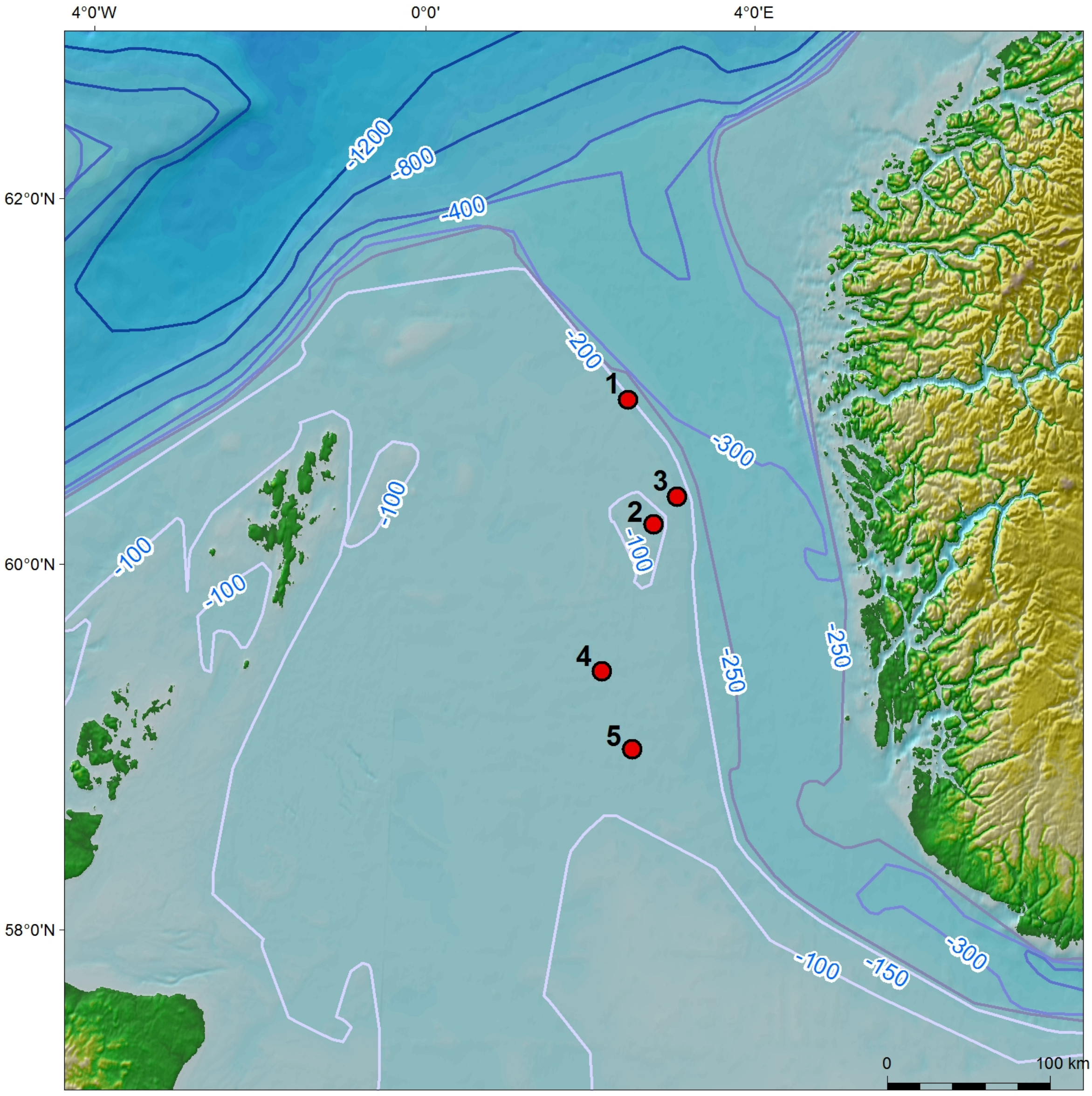
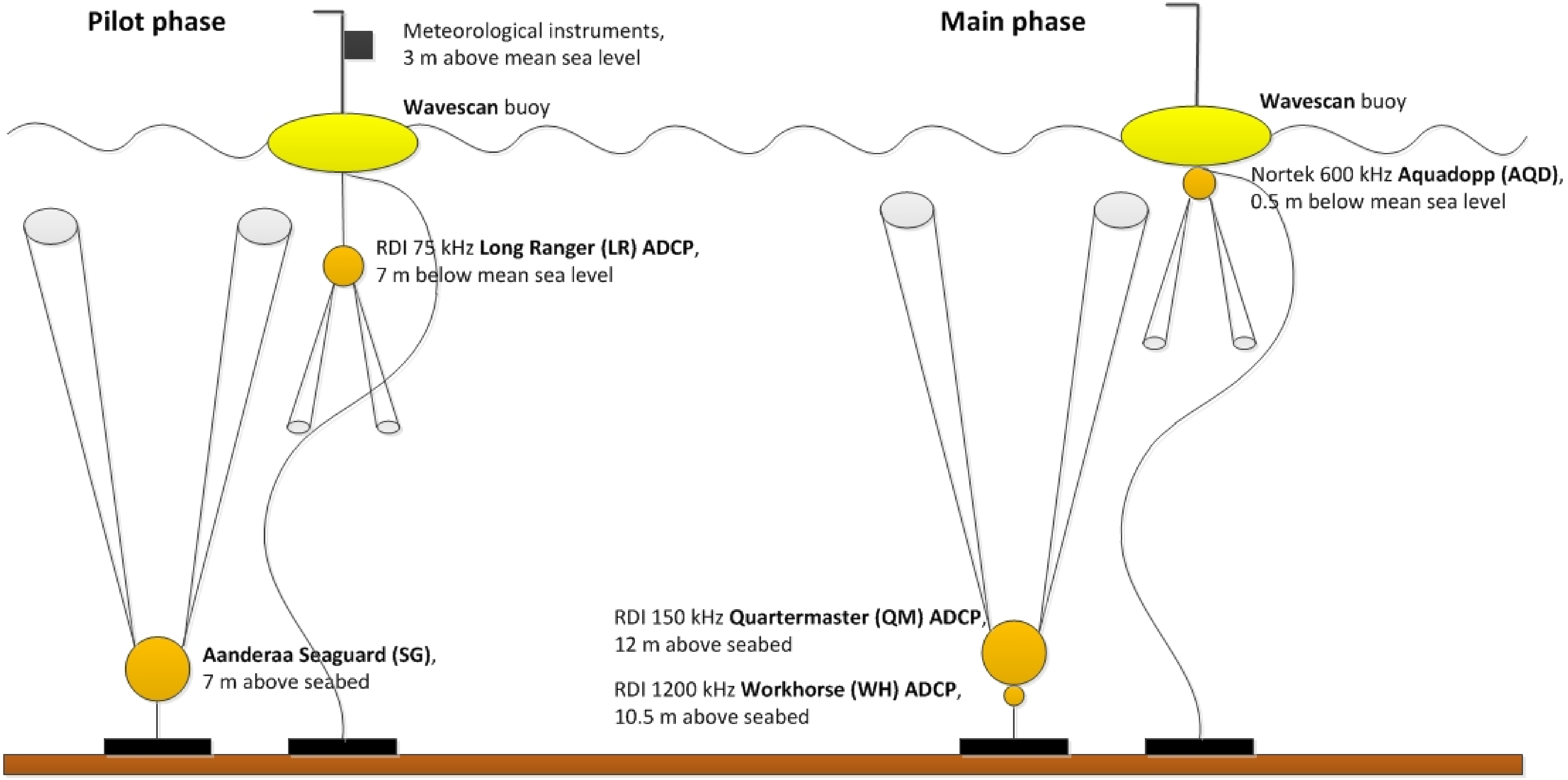
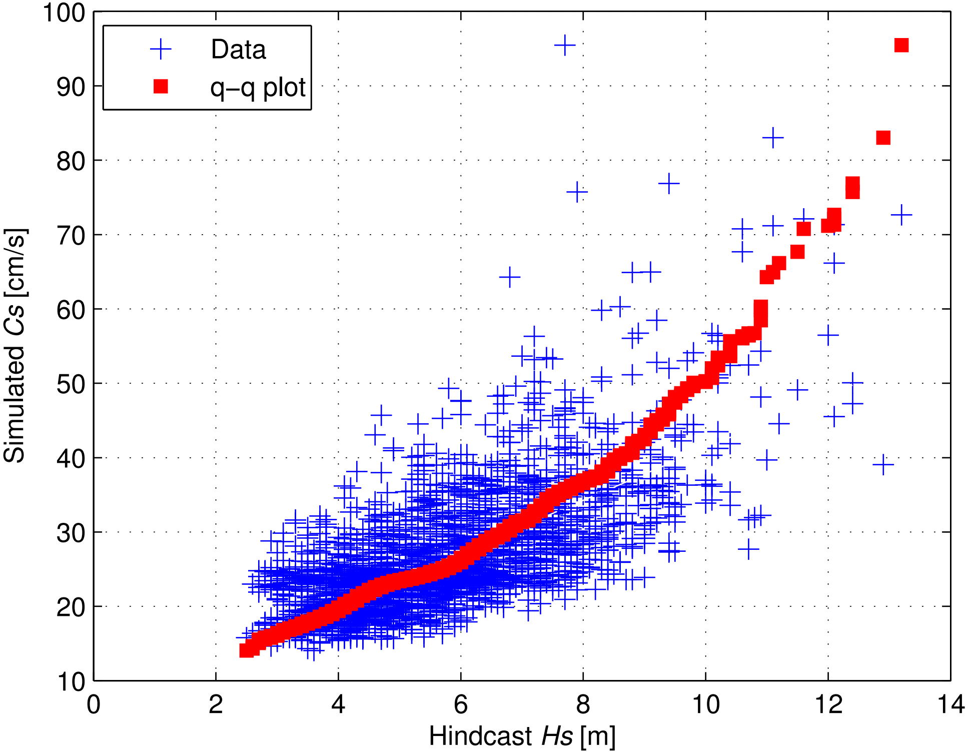


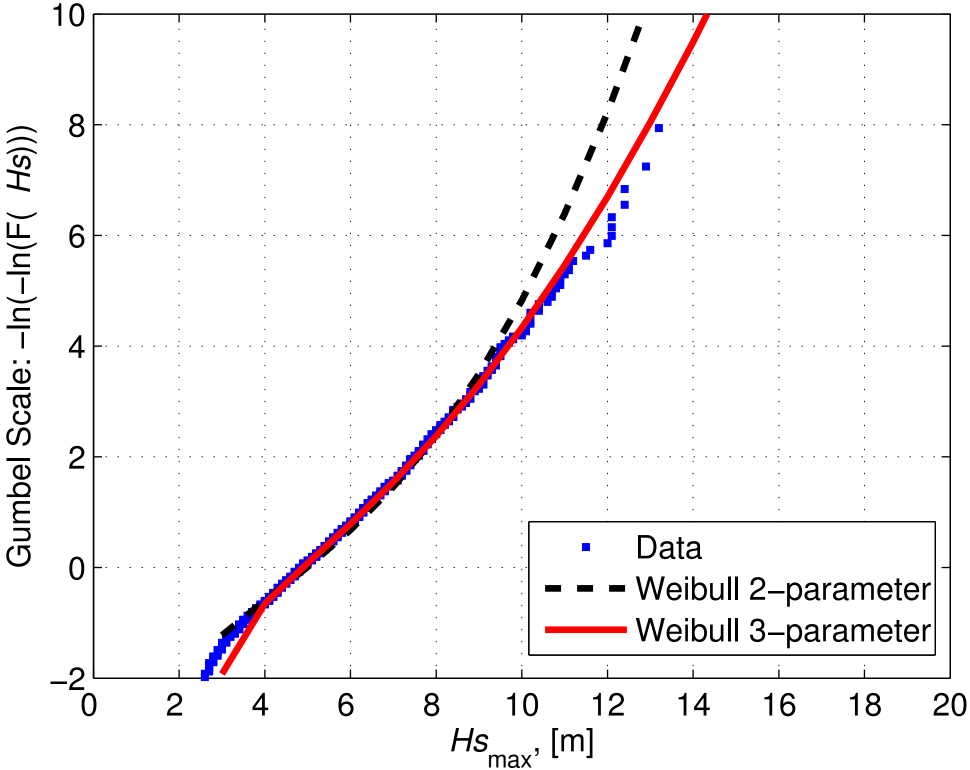
Figure 9 Comparison of empirical (squares) and fitted (dotted) distributions of (I) Hs_{max}, (II) Cs_{max} and (III) mean L in episodes of wind-generated inertial oscillations during the validation period (red), NORA10 period (black) and 5 year partitions of the NORA10 period (blue).



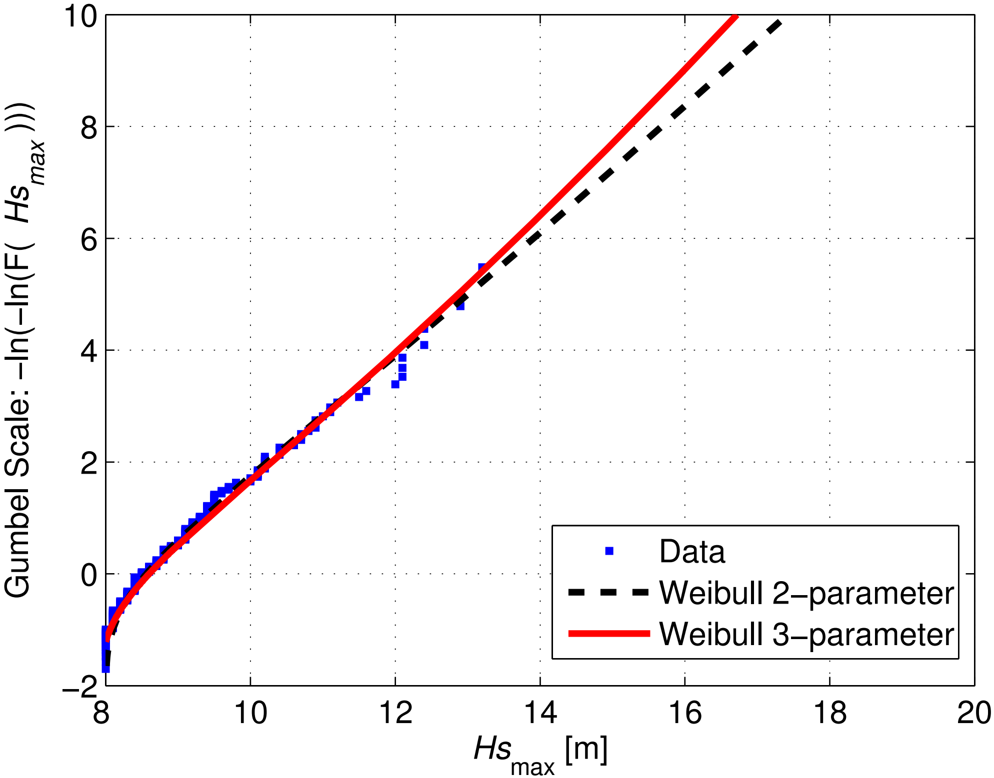
WGS84 UTM zone 31N
Created: 11.04.2016

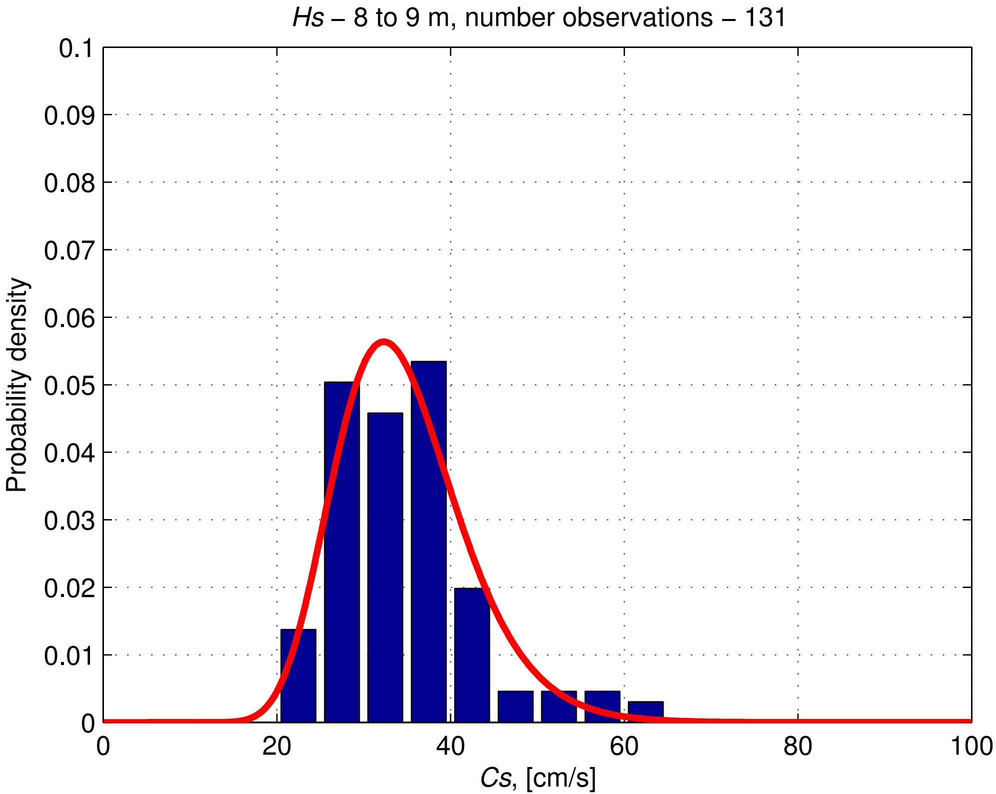

Pilot phase
Meteorological instruments,
3 m above mean sea level
Wavescan buoy
RDI 75 kHz Long Ranger (LR) ADCP,
7 m below mean sea level
Aanderaa Seaguard (SG),
7 m above seabed
Main phase
Wavescan buoy
Nortek 600 kHz Aquadopp (AQD),
0.5 m below mean sea level
RDI 150 kHz Quartermaster (QM) ADCP,
12 m above seabed
RDI 1200 kHz Workhorse (WH) ADCP,
10.5 m above seabed

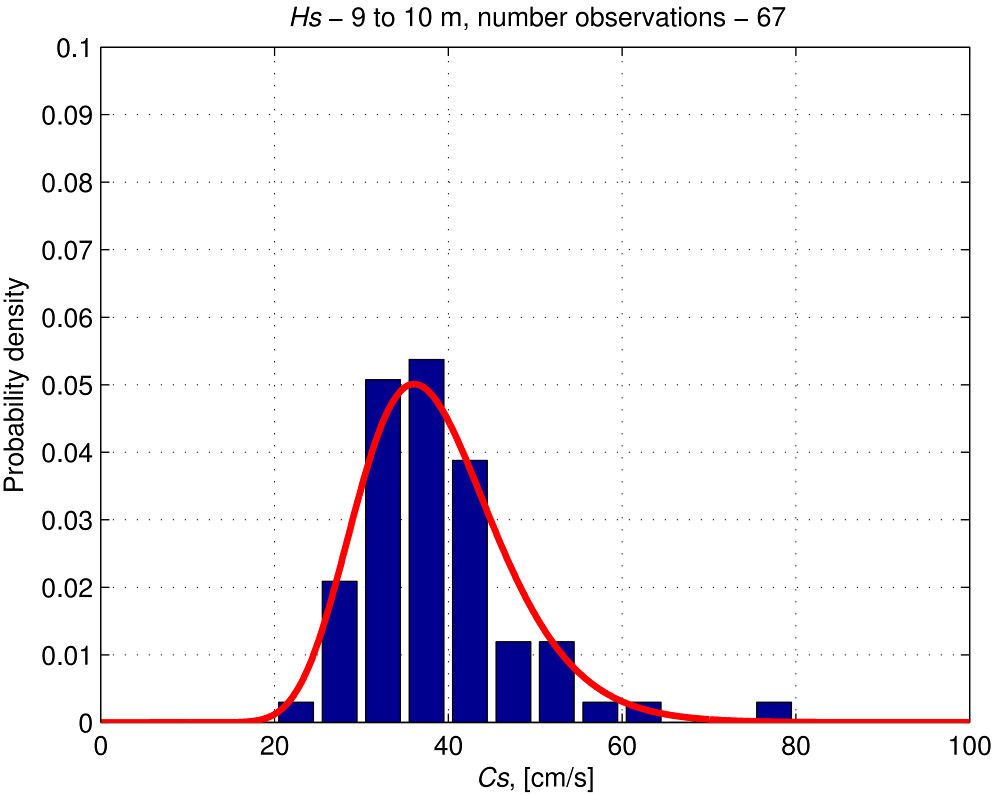

Data
q–q plot
Simulated Cs [cm/s]
Hindcast Hs [m]
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14

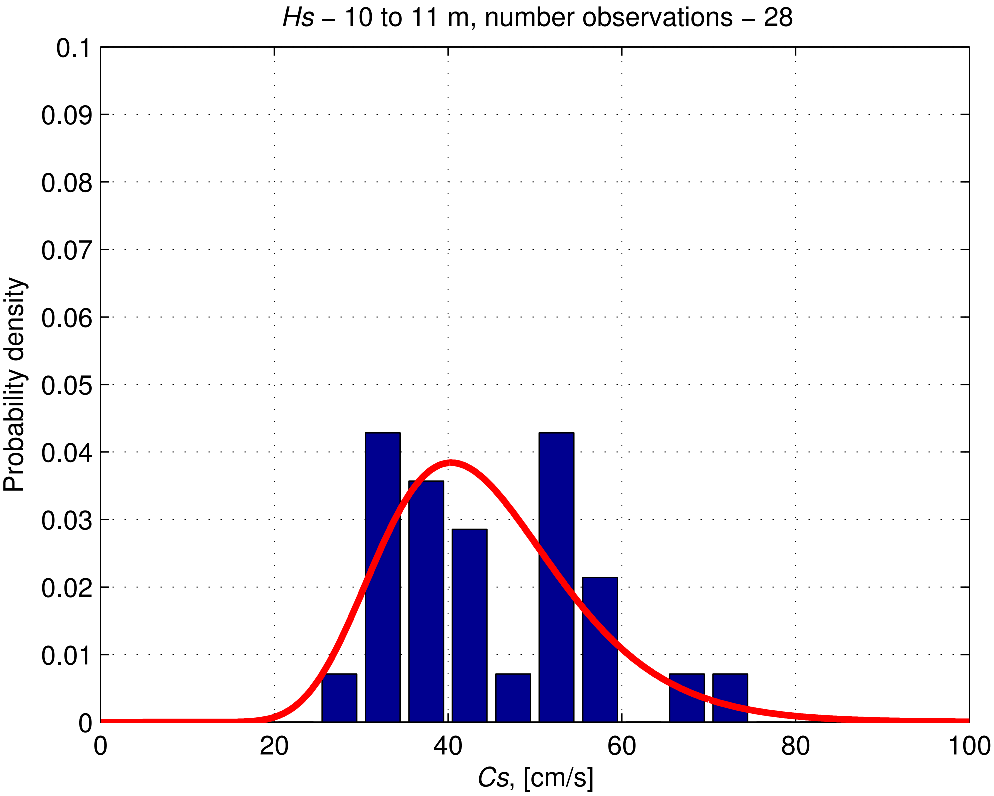


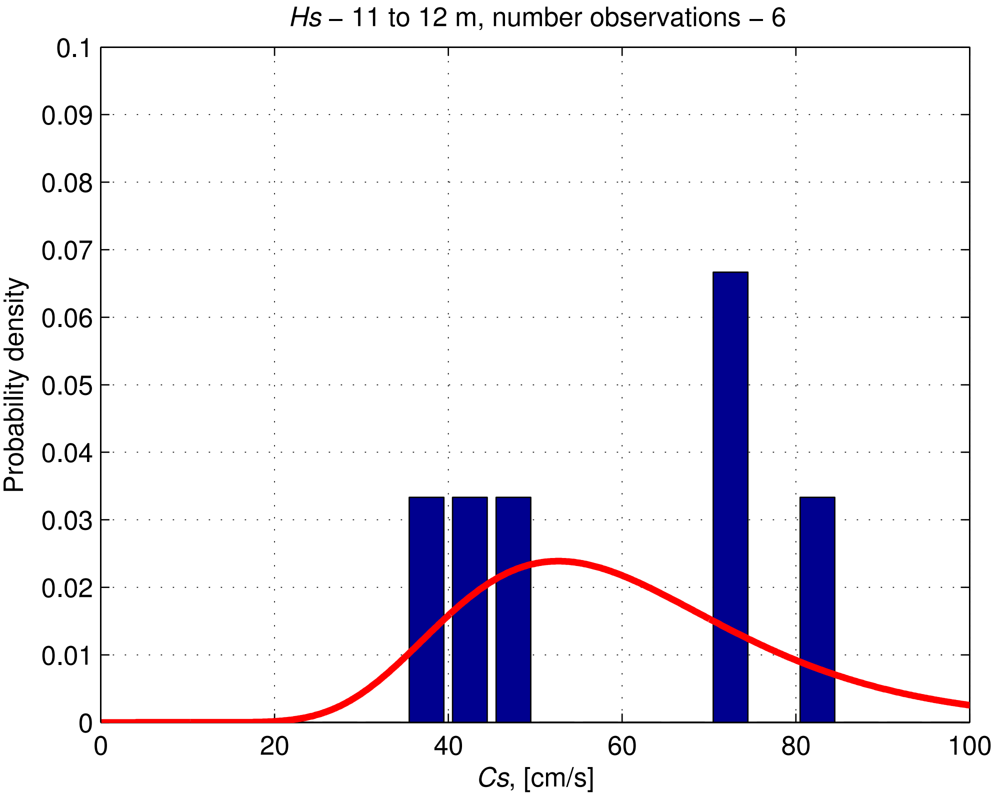
Gumbel Scale: −ln(−ln(F(Hs)))
10
8
6
4
2
0
−2
0
2
4
6
8
10
12
14
16
18
20
Hs_{max}, [m]
Data
Weibull 2−parameter
Weibull 3−parameter

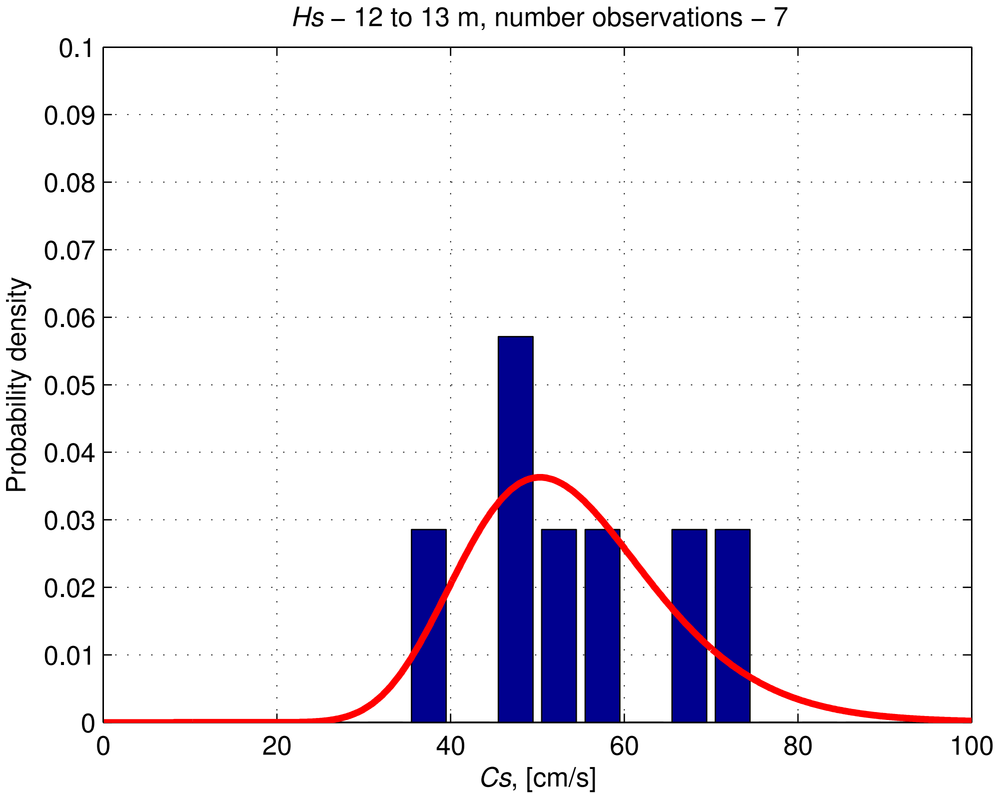

Gumbel Scale: $-\ln(-\ln(F(Hs_{max})))$
Hs_{max} [m]
10
8
6
4
2
0
−2
8
10
12
14
16
18
20
Data
Weibull 2−parameter
Weibull 3−parameter

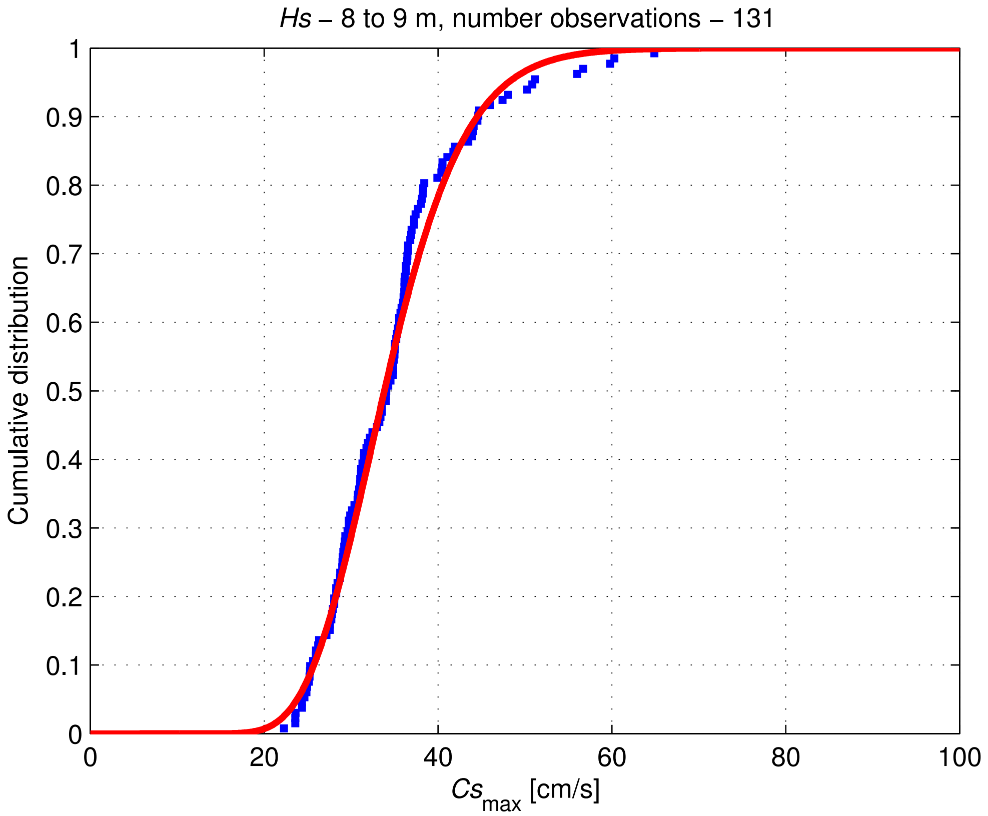

Hs – 8 to 9 m, number observations – 131
Probability density
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
Cs, [cm/s]

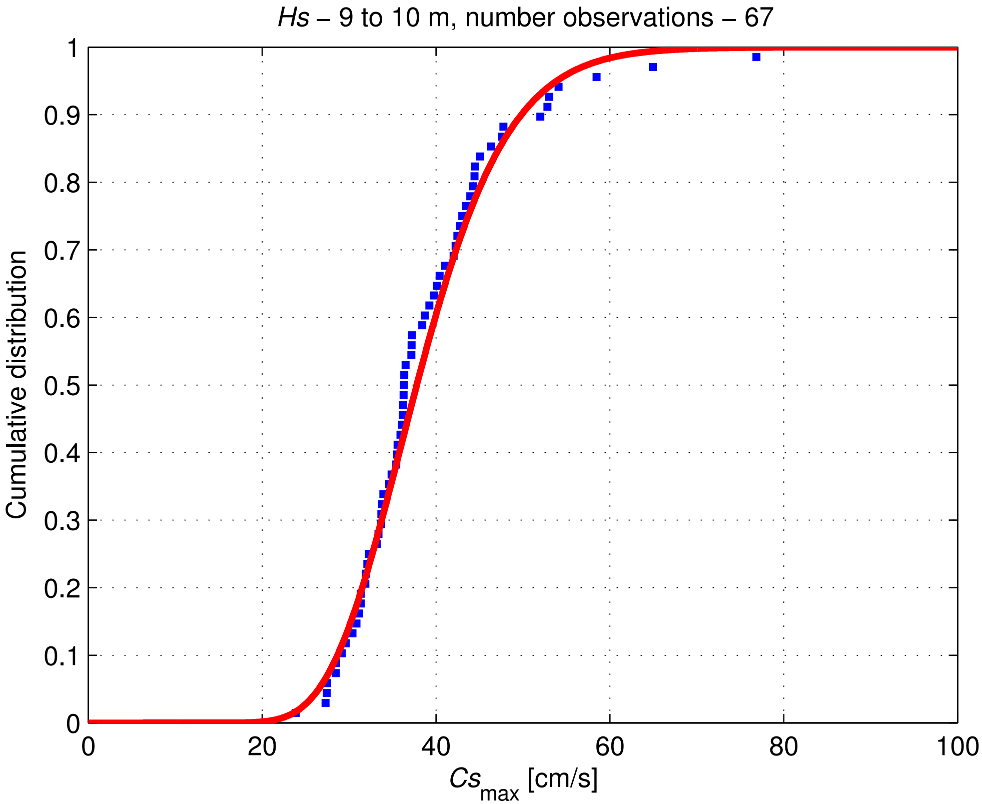

Hs – 9 to 10 m, number observations – 67
Probability density
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
Cs, [cm/s]

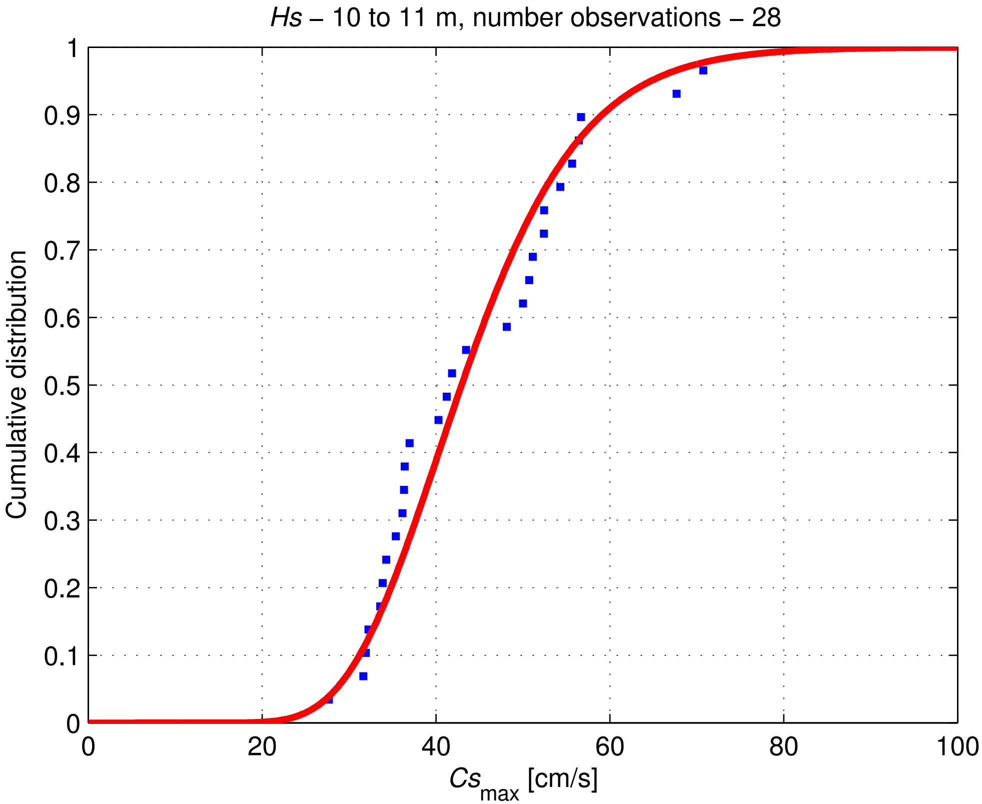

Hs – 10 to 11 m, number observations – 28
Probability density
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
Cs, [cm/s]

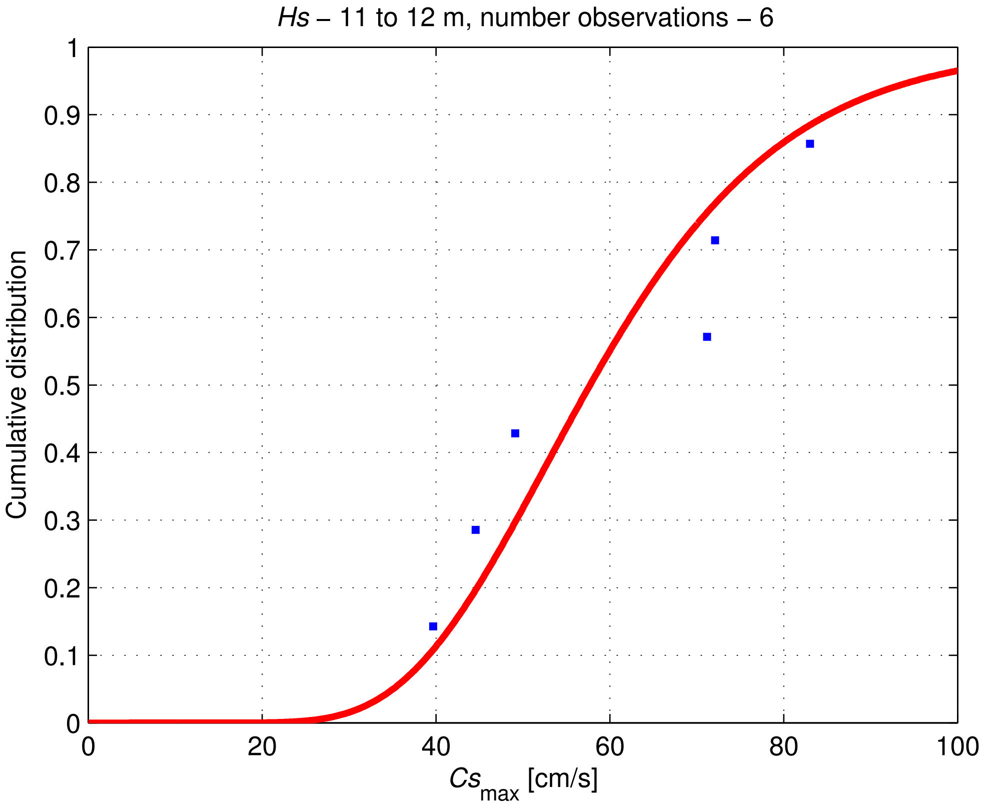

Hs – 11 to 12 m, number observations – 6
Probability density
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
20
40
60
80
100
Cs, [cm/s]


Hs – 12 to 13 m, number observations – 7
Probability density
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
Cs, [cm/s]

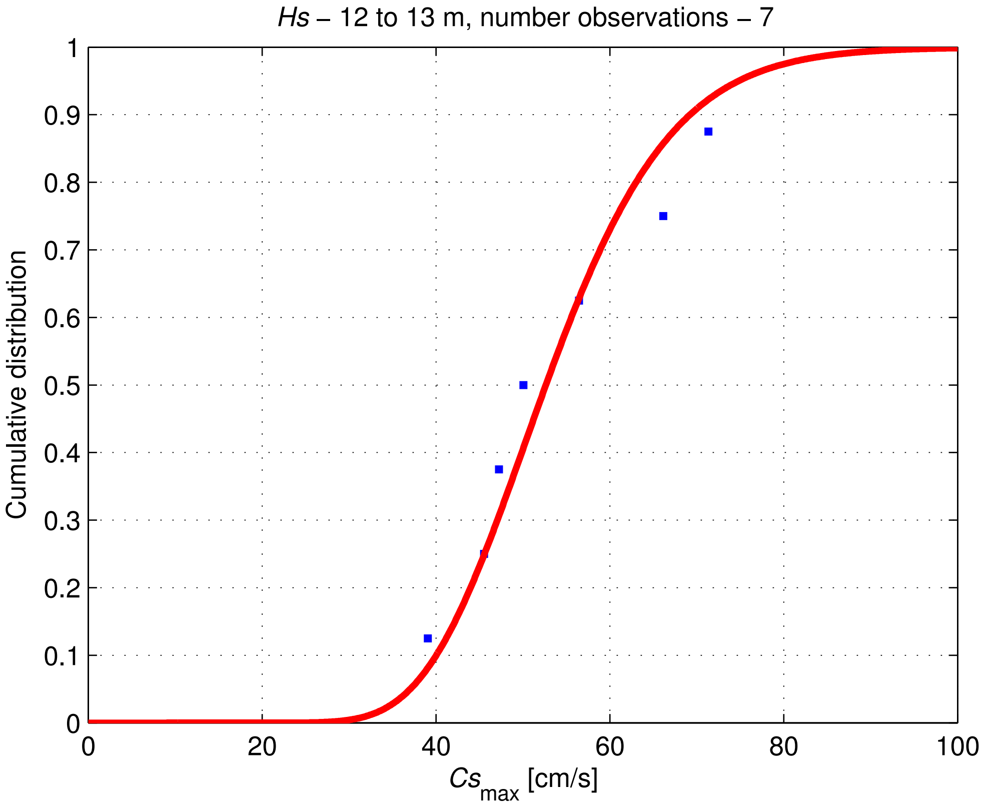

Hs – 8 to 9 m, number observations – 131
Cumulative distribution
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
*Cs*max [cm/s]

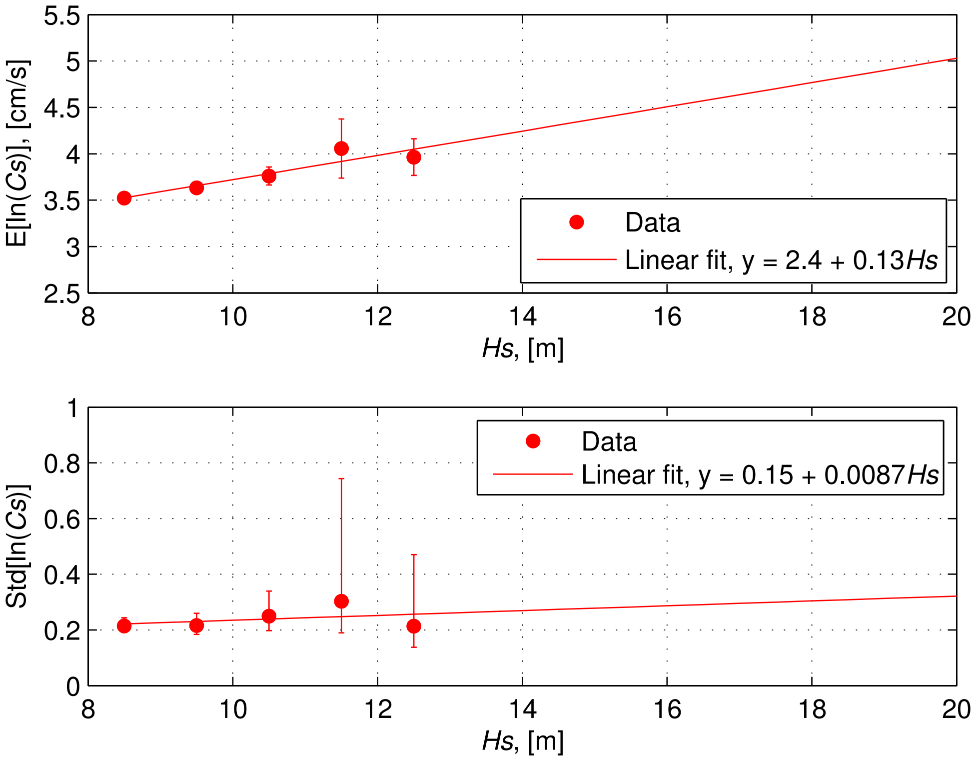
*Hs* – 9 to 10 m, number observations – 67
Cumulative distribution
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
Cs_{max} [cm/s]

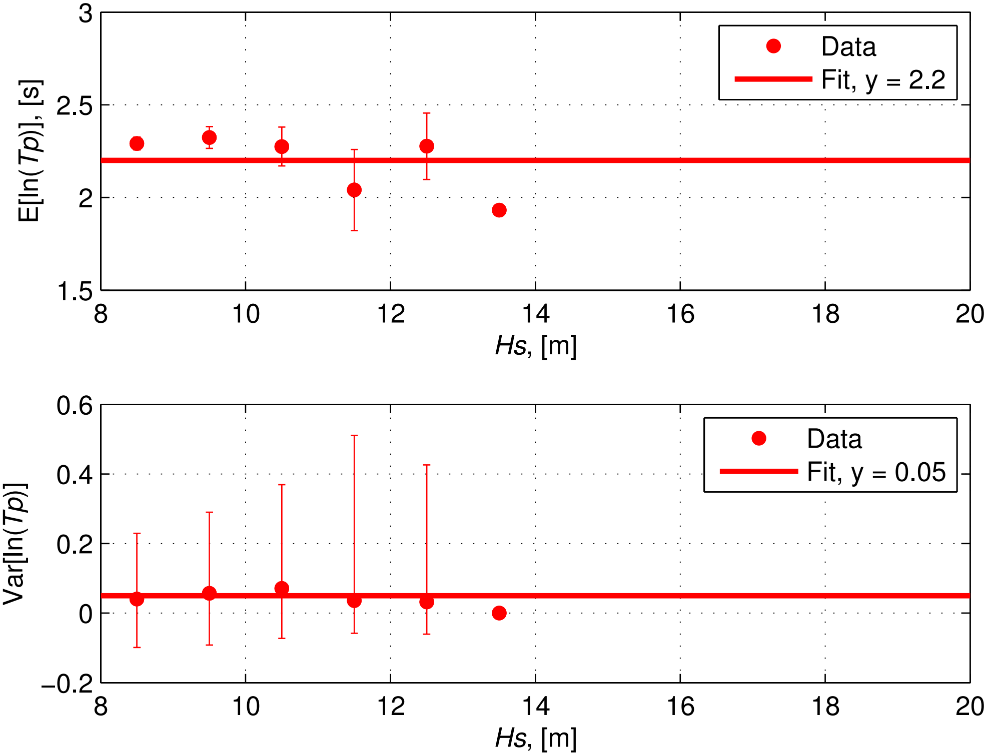

Hs – 10 to 11 m, number observations – 28
Cumulative distribution
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
Cs_{max} [cm/s]



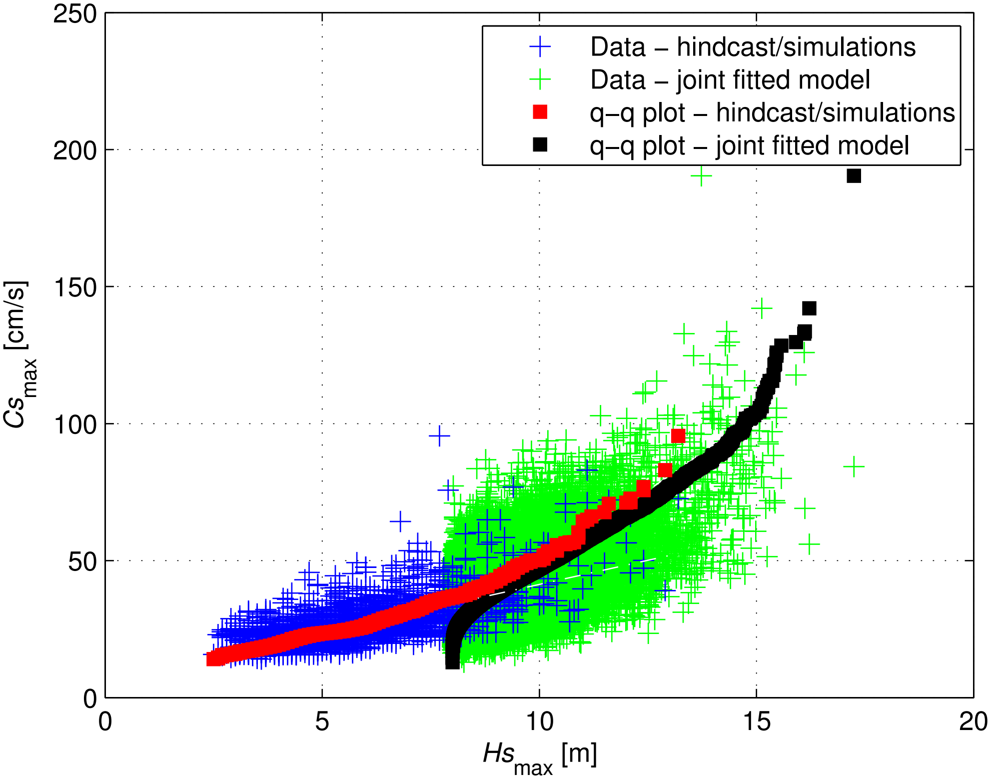
Hs – 11 to 12 m, number observations – 6
Cumulative distribution
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
Cs_{max} [cm/s]


Hs – 12 to 13 m, number observations – 7
Cumulative distribution
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
Cs_max [cm/s]

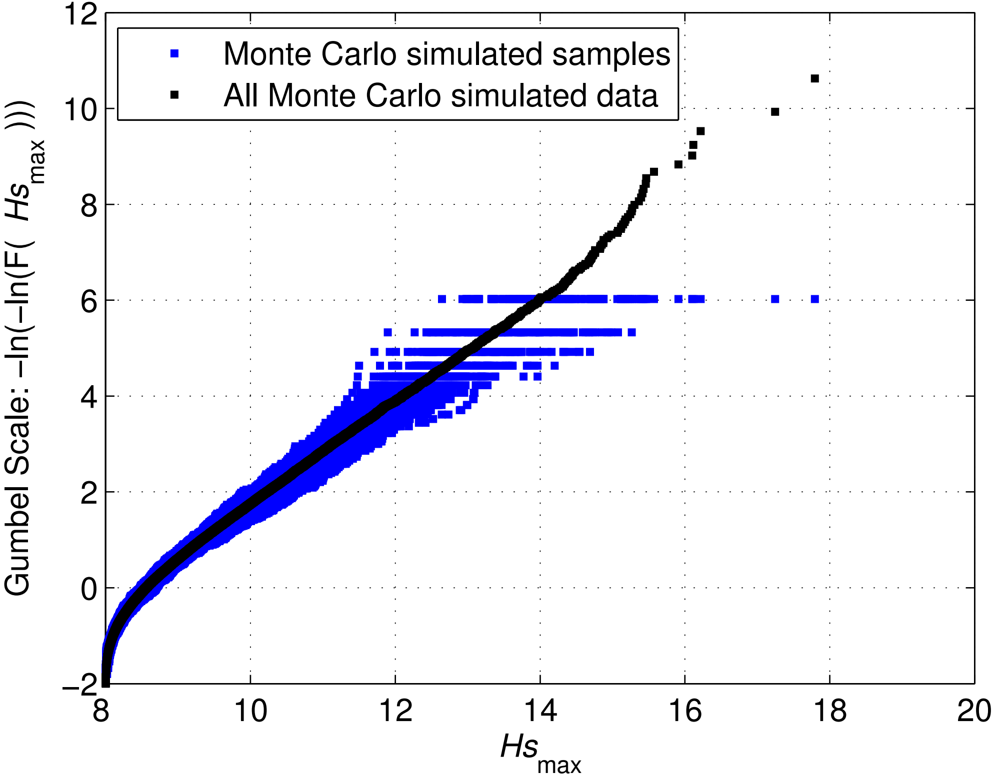

5.5
5
4.5
4
3.5
3
2.5
E[ln(Cs)], [cm/s]
8
10
12
14
16
18
20
Hs, [m]
● Data
Linear fit, y = 2.4 + 0.13Hs
1
0.8
0.6
0.4
0.2
0
Std[ln(Cs)]
8
10
12
14
16
18
20
Hs, [m]
● Data
Linear fit, y = 0.15 + 0.0087Hs

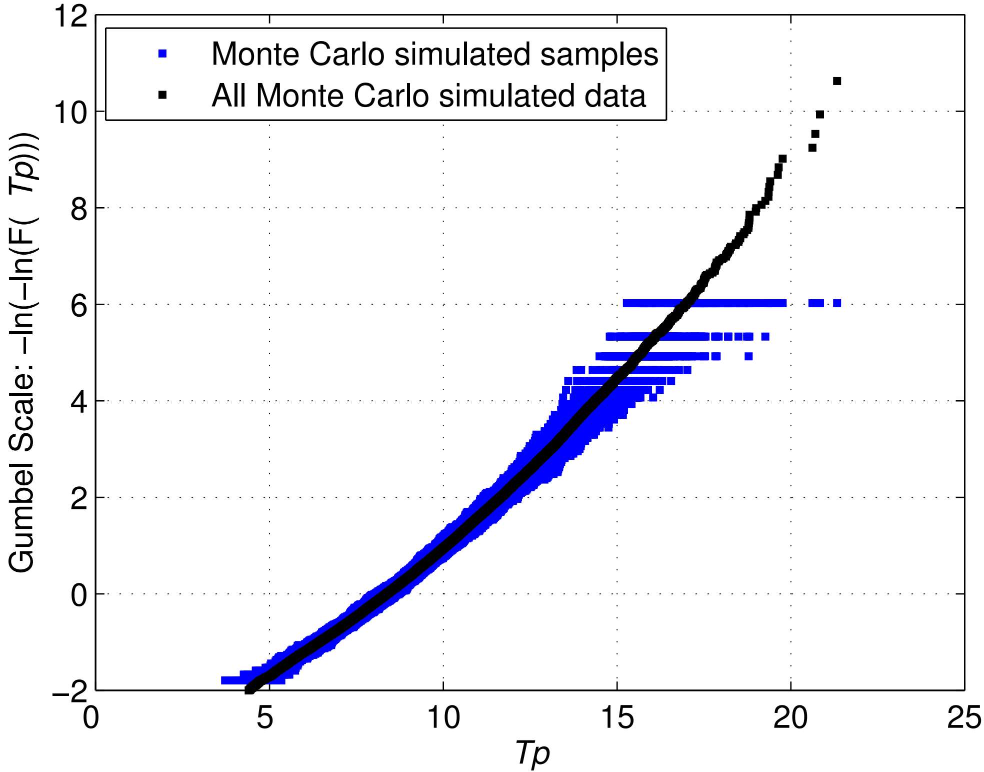


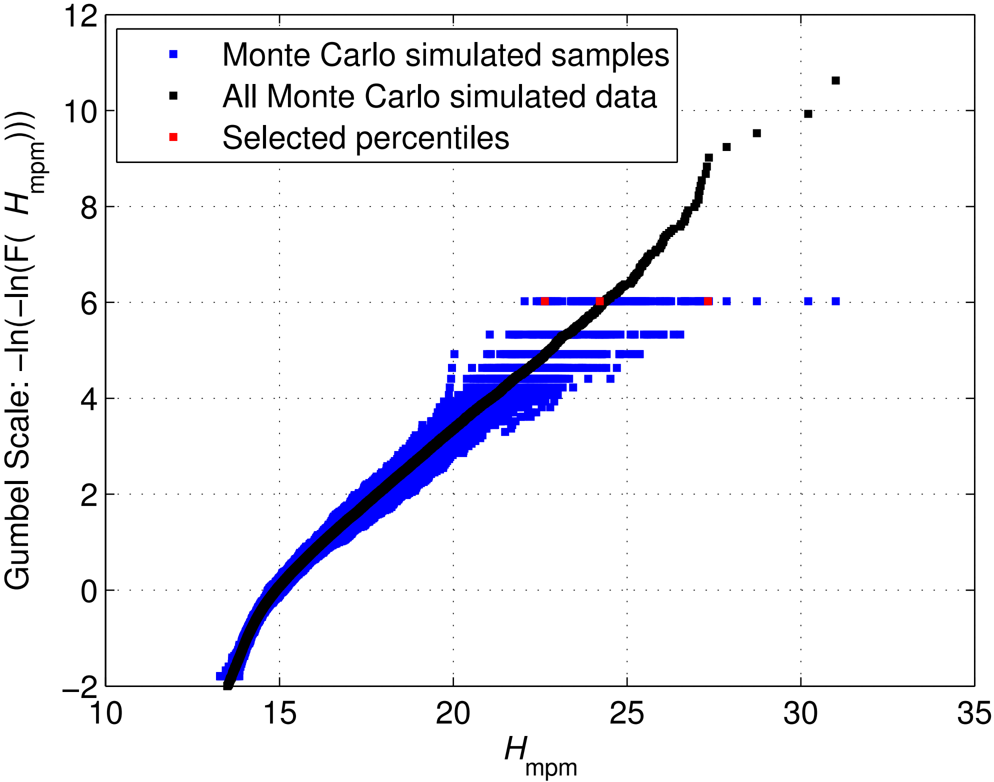
3
2.5
2
1.5
E[ln(*Tp*)], [s]
8
10
12
14
16
18
20
Hs, [m]
Data
Fit, y = 2.2
0.6
0.4
0.2
0
−0.2
Var[ln(*Tp*)]
8
10
12
14
16
18
20
Hs, [m]
Data
Fit, y = 0.05



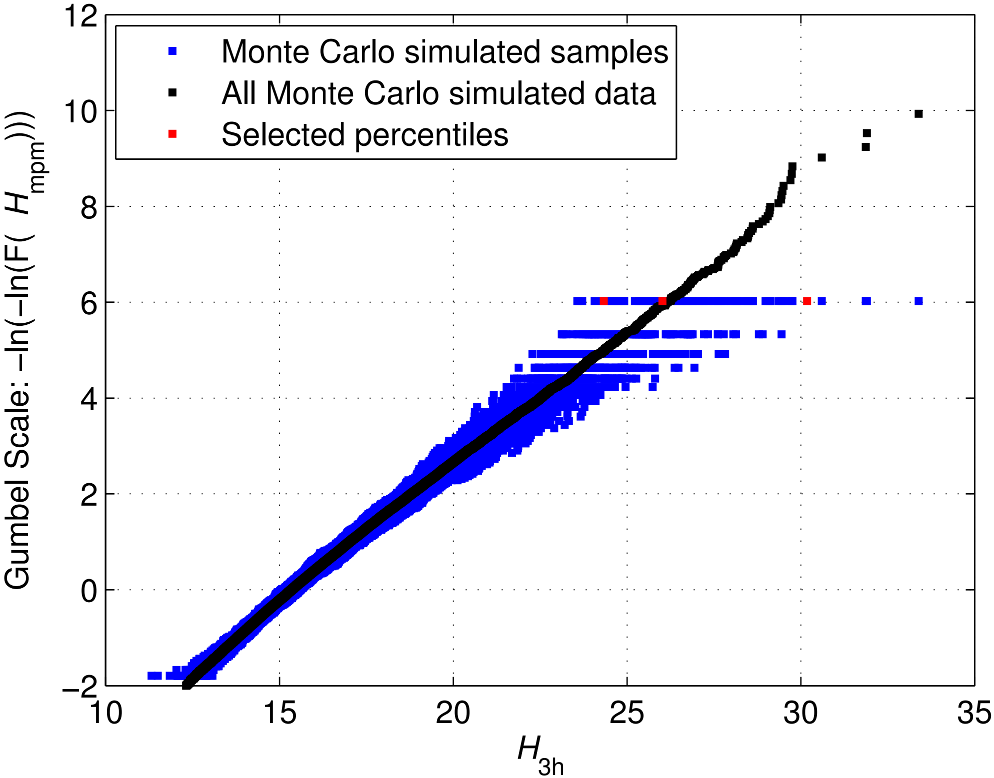
250
200
150
100
50
0
0
5
10
15
20
Cs_{max} [cm/s]
Hs_{max} [m]
Data – hindcast/simulations
Data – joint fitted model
q–q plot – hindcast/simulations
q–q plot – joint fitted model

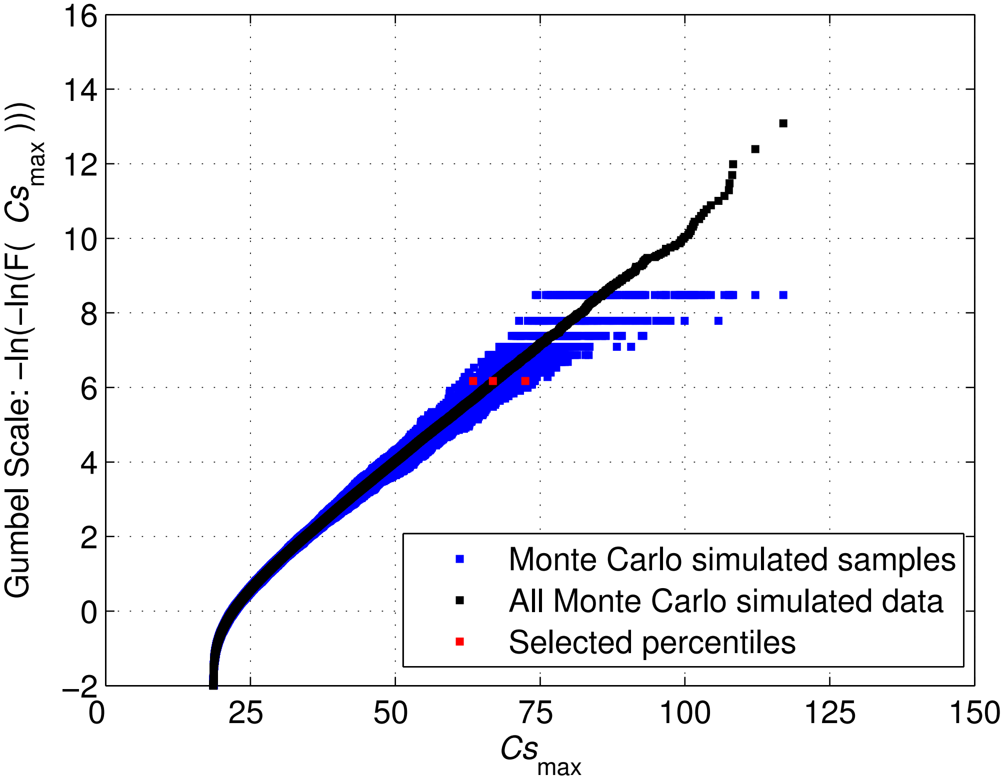

Monte Carlo simulated samples
All Monte Carlo simulated data
Gumbel Scale: −ln(−ln(F(Hs_{max})))
Hs_{max}
12
10
8
6
4
2
0
−2
8
10
12
14
16
18
20

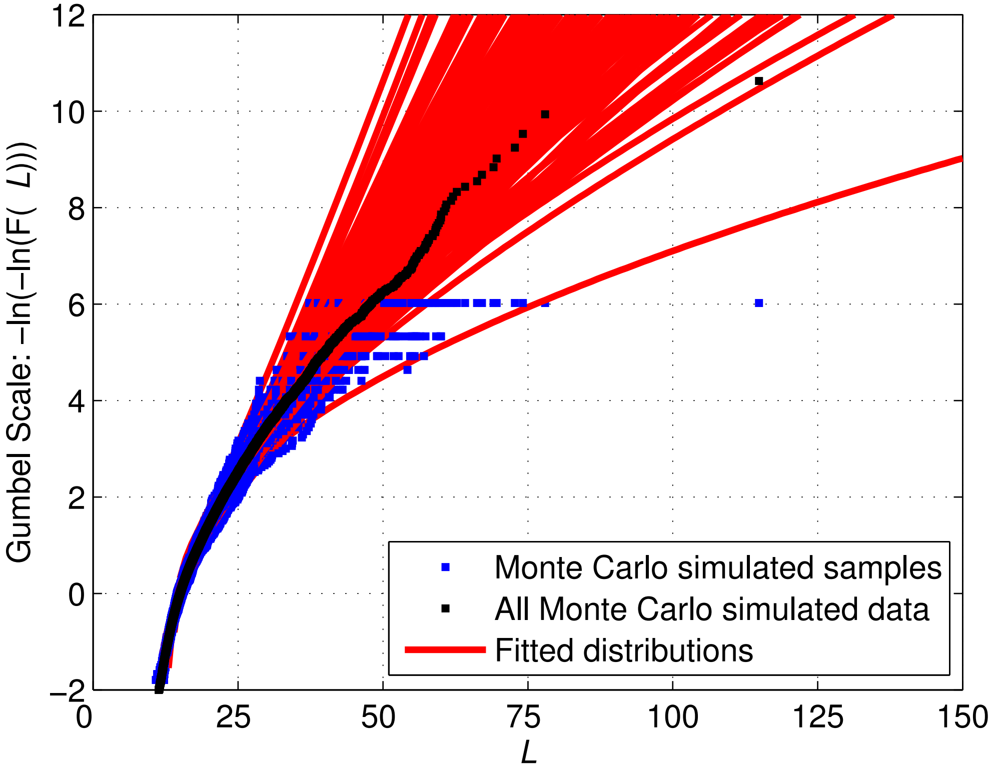

Monte Carlo simulated samples
All Monte Carlo simulated data
Gumbel Scale: −ln(−ln(F(Tp)))
Tp
12
10
8
6
4
2
0
−2
0
5
10
15
20
25

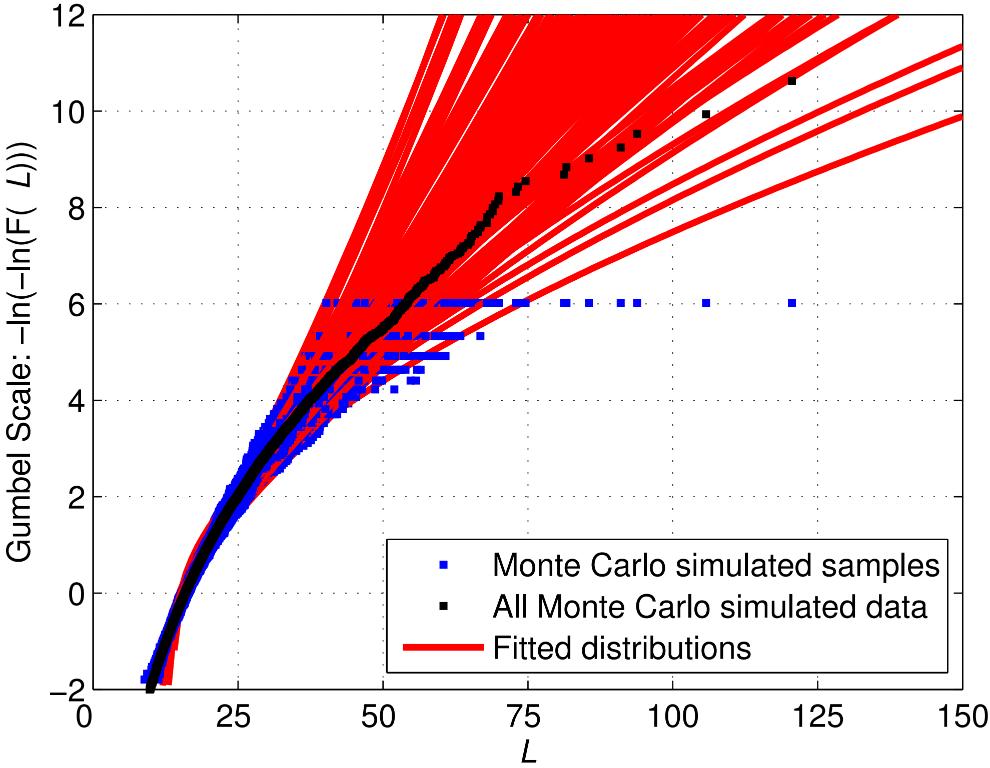


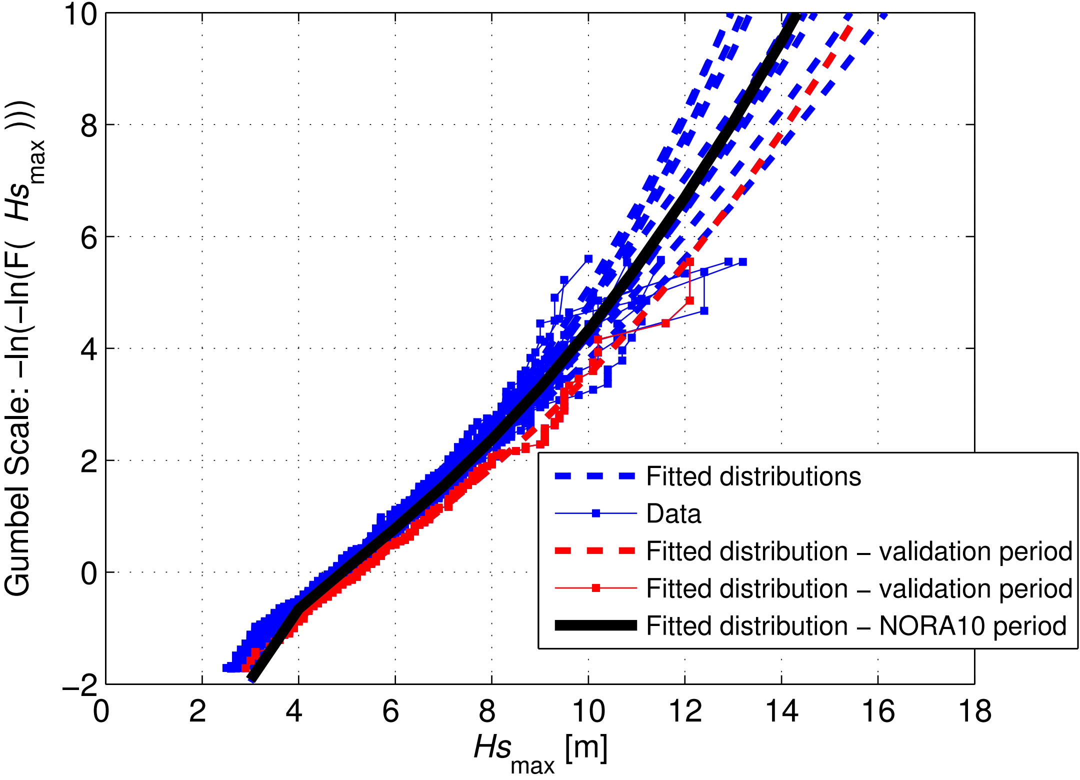
Monte Carlo simulated samples
All Monte Carlo simulated data
Selected percentiles
Gumbel Scale: −ln(−ln(F(H_{mpm})))
H_{mpm}
12
10
8
6
4
2
0
−2
10
15
20
25
30
35

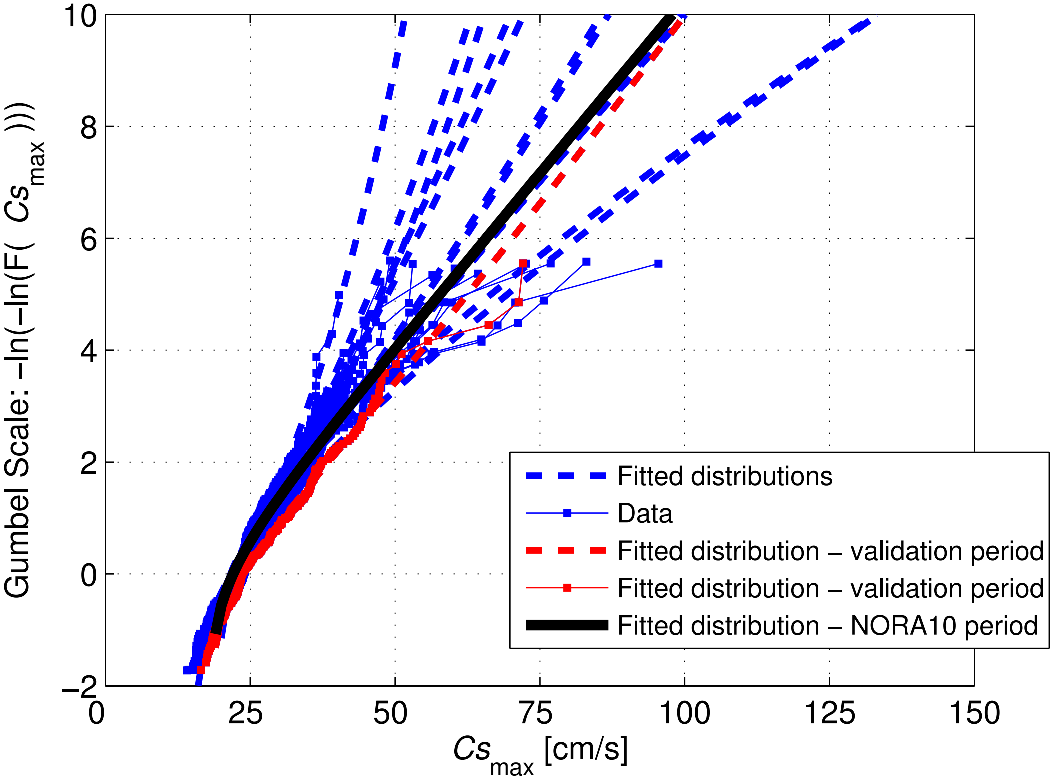

Monte Carlo simulated samples
All Monte Carlo simulated data
Selected percentiles
Gumbel Scale: −ln(−ln(F(H_{mpm})))
H_{3h}
12
10
8
6
4
2
0
−2
10
15
20
25
30
35

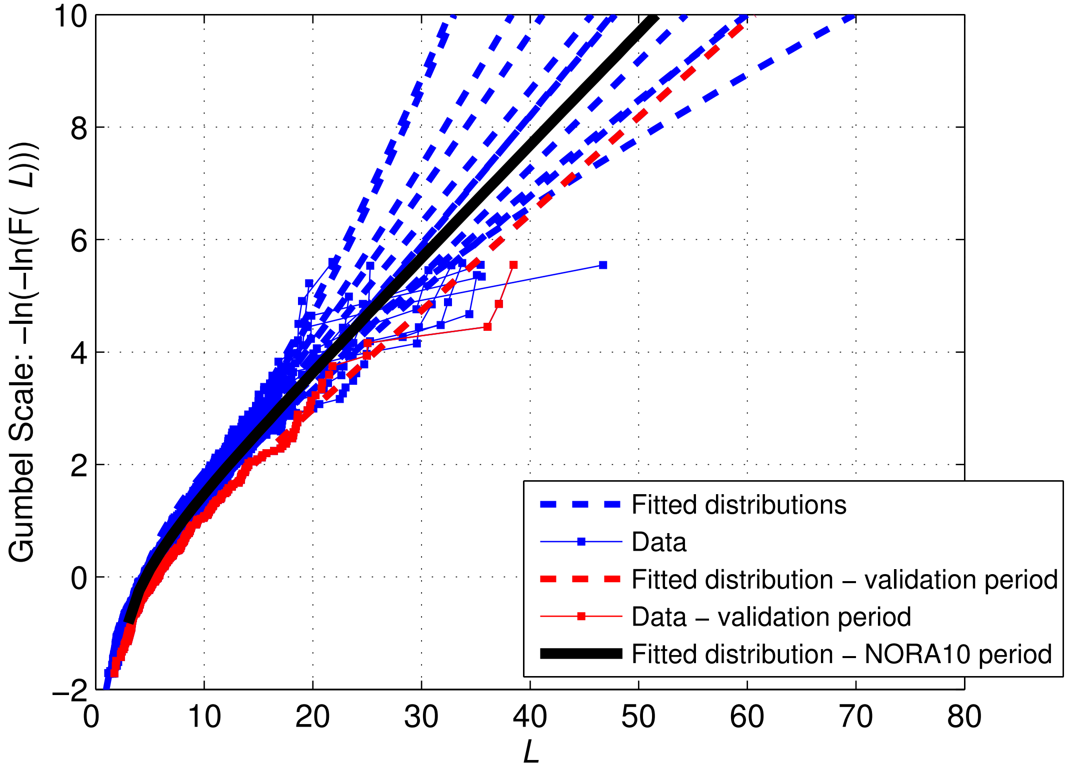

Gumbel Scale: −ln(−ln(F(Cs_max)))
16
14
12
10
8
6
4
2
0
−2
0
25
50
75
100
125
150
Cs_max
Monte Carlo simulated samples
All Monte Carlo simulated data
Selected percentiles


Gumbel Scale: −ln(−ln(F(L)))
12
10
8
6
4
2
0
−2
0
25
50
75
100
125
150
L
Monte Carlo simulated samples
All Monte Carlo simulated data
Fitted distributions


Gumbel Scale: −ln(−ln(F(L)))
12
10
8
6
4
2
0
−2
0
25
50
75
100
125
150
L
Monte Carlo simulated samples
All Monte Carlo simulated data
Fitted distributions


Gumbel Scale: −ln(−ln(F(Hs_max)))
Hs_max [m]
10
8
6
4
2
0
−2
0
2
4
6
8
10
12
14
16
18
Fitted distributions
Data
Fitted distribution – validation period
Fitted distribution – validation period
Fitted distribution – NORA10 period


Gumbel Scale: −ln(−ln(F(Cs_{max})))
10
8
6
4
2
0
−2
0
25
50
75
100
125
150
Cs_{max} [cm/s]
Fitted distributions
Data
Fitted distribution − validation period
Fitted distribution − validation period
Fitted distribution − NORA10 period


Gumbel Scale: −ln(−ln(F(L)))
L
10
8
6
4
2
0
−2
0
10
20
30
40
50
60
70
80
Fitted distributions
Data
Fitted distribution – validation period
Data – validation period
Fitted distribution – NORA10 period