

# Extreme Events in Field Data and in a Second Order Wave Model

Elzbieta Maria Bitner-Gregersen<sup>1</sup>, and Anne Karin Magnusson<sup>2</sup>

<sup>1</sup> Det Norske Veritas, Veritasveien 1,  
N-1322 Høvik, Norway  
elzbieta.bitner-gregersen@dnv.com  
<sup>2</sup> Norwegian Meteorological Institute, Allégaten 70,  
N-5007 Bergen, Norway  
a.k.magnusson@met.no

**Abstract.** The analysis is based on North Sea field data and on second order time domain simulations. Statistical properties of extreme waves are presented. Particular focus is given to the wave crest. Wave parameters obtained from the field data are compared with the values derived from the second order time domain simulations. Limitations of the 2<sup>nd</sup> order wave model to predict extreme events are shown. Uncertainties related to the field and numerically generated data are discussed.

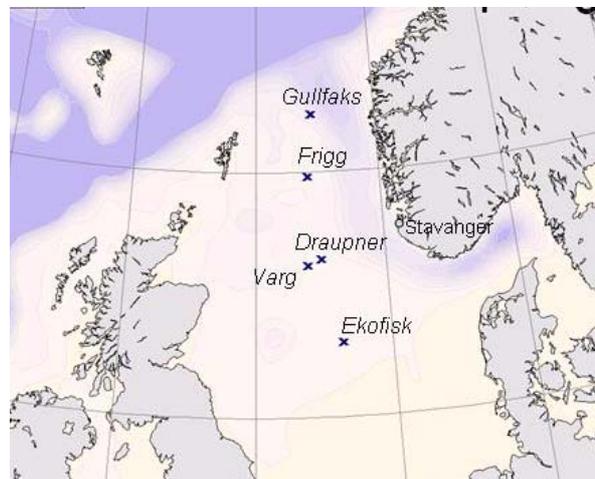
## 1 Introduction

Abnormal waves, often called *rogue* waves or *freak* waves have been subject to much attention recently. These waves represent operational risks to ship and offshore structures, and are likely to be responsible for a number of accidents in the past. The completed (in 2003) EU research project MaxWave has made significant contribution to the understanding of freak waves; however, several important questions are still not answered. Too few data sets including freak events have been recorded making difficult to develop satisfactory physical and statistical models for prediction of these waves. Further, no consensus has been reached neither about a definition of a freak event nor about the probability of occurrence of freak waves. Finally, still more research is called for in order to investigate effects of these waves on marine structures.

The random nature of sea surface and non-linear effects are important when analyzing extreme events. Higher order solutions increase wave steepness, maximum crest and wave height compared to linear theory, and consequently also increase the probability of occurrence of extreme waves. As shown by several authors (i.e. [17], [9], [2]), freak waves in the “second order world” are pretty rare events. At the 100-year crest level the 2<sup>nd</sup> order models are expected to be of reasonable accuracy to predict extreme events, see [4].

The present analysis is based on North Sea field data and on second order time domain simulations using measured sea state parameters. The study focuses on statistical properties of extreme waves and on limitations of the 2<sup>nd</sup> order wave model to predict them. Main attention is given to the wave crest. Time series of wave elevations are generated using the Pierson-Moskowitz [16], JONSWAP [9] and two-peak Torsethaugen [19] frequency spectral shapes for long-crested seas and deep/intermediate water depth. Measured wave parameters are compared with values given by the second order time domain simulations. Sampling variability related to the data is discussed.

## 2 Field Data



**Fig. 1** The North Sea with locations of Ekofisk, Varg, Draupner, Sleipner, Frigg and Gullfaks.

Field data from two sites (Ekofisk and Draupner) in the North Sea are used. The following storms have been chosen as background for the study:

- (1) 25-26 October 1998: The ‘Stenfjell case’, using data at Ekofisk. The case is named after the bulk carrier *Stenfjell*, which arrived at Esbjerg (a harbour on West coast of Denmark) on the morning of 26 October 1998 with heavy weather damage to the wheelhouse, accommodation and electrical installations, reportedly due to freak waves. The ship was sailing from Hamburg to Tananger (near Stavanger, Western Norway). The ship experienced wind and waves from a low that had passed over the central North Sea, giving strong winds in a constricted area on the South of the low. The area moved from the East of Scotland towards the Danish coast passing over Ekofisk where a sharp increase in wave height ( $H_s=10\text{m}$ ) was observed on the 25th. Some high crests are measured by lasers at two locations of the site and are analysed further herein.

(2) *27 December 1998*: A situation with close to 12m significant wave height with westerly winds at Ekofisk. High crests are observed in measured time series. The fetch is short from this direction and the increase is sharp.

(3) *5-6 February 1999*: The production ship (FPSO) at Varg (58N, 2E), operated by Saga Petroleum, experienced some damage due to ‘green water’ [5]. The wave damage caused the loss of a life buoy, a fire equipment storage locker torn from the connections and minor damages to cable gates occurred. All these items were located at the mid-ship. Time of incidence is not known. At Ekofisk, about 160 km further South, waves increased rapidly from 5 to 9m in a 6 hours period, with winds from between W and WNW. Wind speed stayed thereafter stable around 22-25 m/s during the night (a 12 hour period), slackening a little (to 20-23 m/s). At around 4 a.m. the 5<sup>th</sup>, wind direction veered to NNW and a high crest is recorded at Ekofisk at 04:40 UTC.

(4) *30 November 1999*: FPSO Varg B experienced some damage due to ‘green water’ [5]. Norsk Hydro reported damage to gas sensors, fire hose cabinets, doors on deluge stations for chemical injection module. Time of incident is not known, but records at Ekofisk also give some high crests. One record with  $Crx/Hs = 1.4$  is used in this study, which occurred in the growing phase of the storm. The record is discussed further below.

(5) *29-30 January 2000*: the Petrojarl Varg ship, operated by Norsk Hydro, experienced damage on fore ship, midship and aft ship [5]. The incident is regarded as the most critical event so far on the Norwegian sector. The strong winds in the South area of the low pressure also influenced Ekofisk. Wave heights increased to about 11m. Some high crests are observed when wind speed is at its maximum (25 m/s from 17 to 21 UTC, from 280 deg). At that time it is most likely that waves are unidirectional.

(6) *1 January 1995*: The ‘Draupner wave’ with a crest height of 18.5 m above mean sea level is recorded by Statoil at the Draupner platform [11]. During this storm several wave heights (trough- to crest heights) more than twice  $H_s$  were observed at the Frigg platform operated by Elf Aquitaine. Analysis of weather maps indicates that there is swell added onto the wind sea from a slightly different direction.

The storms listed above have been selected from the MaxWave storm database [14]. Note that apart of the Draupner January 1 event all storms were recorded at the Ekofisk platform (see Fig.1). Sampling frequency used at Ekofisk is 2Hz, at Draupner 2.133 Hz. There are three sensors at Ekofisk: a waverider, and 2 downlooking lasers; the laser data are used herein. Wave data at Draupner are measured with a laser. The water depth for both platforms is 70m. One to two wave records (see Table 1) with the most extreme events present have been chosen from each storm and analyzed herein. In Table 1  $H_{4std}$  denotes significant wave height calculated from the time series and is equal to 4 times standard deviation of the sea surface while  $H_{m0}$  represents significant wave height obtained from the zero-spectral moment of the whole time series. Although recognized

software is used to calculate  $H_{4std}$  and  $H_{m0}$ , a significant difference between the two estimators can be observed.

**Table 1. Wave records selected for the study.**

Case	Date and time	$H_{4std}$ (m)	$H_{m0}$ (m)	$T_p$ (s)	$T_{m02}$ (s)
1	25 Oct. 1998, 16:00 UTC	9.2	8.8	12.6	9.2
2	27 Dec. 1998, 06:40 UTC	11.6	10.4	14.6	10.6
3	5 Feb. 1999, 04:40 UTC	8.1	7.6	13.0	9.1
4	1 Dec. 1999, 02:20 UTC	6.5	7.2	11.3	8.7
5	29 Jan. 2000, 18:40 UTC	10.5	12.1	12.2	8.8
6	1 Jan. 1995, 15:20 UTC	11.9	11.2	16.7	10.8
7	1 Jan. 1995, 23:00 UTC	6.1	5.7	9.8	6.9

### 3 Second Order Simulations

A simulation program documented by Birknes and Bitner-Gregersen [1] is applied. Time series of wave elevations are generated using three empirical spectra: Pierson-Moskowitz [16], JONSWAP [9] and Torsethaugen [19]. The wave amplitudes are given by

$$a = \sqrt{2S(\omega, \theta)D(\theta)\Delta\omega\Delta\theta} \quad (1)$$

in the case of a directional sea state. Assuming single peaked frequency spectrum, e.g. JONSWAP, the spectrum can be given as  $S(\omega, \theta) = S(\omega) D(\theta)$ . For a two-peaked spectrum, we use  $S(\omega, \theta) = S_1(\omega) D_1(\theta) + S_2(\omega) D_2(\theta)$ .  $S_1$  and  $S_2$  may represent swell and wind sea frequency spectra and  $D_1$  and  $D_2$  are corresponding spreading functions.

Random wave amplitudes and random phases are generated for each wave component. The phases are assumed uniform distributed on the interval  $[0, 2\pi]$ , and the amplitudes are Rayleigh distributed with mean-square value given by

$$E[a^2] = 2S(\omega)\Delta\omega \quad (2)$$

The wave amplitude and phase define the complex wave amplitude through the following relation

$$A = a \exp(i\varepsilon) \quad (3)$$

A convenient model for combined seas is simply to add two frequency spectra

$$S(f) = S_{sw}(f) + S_w(f) \quad (4)$$

where  $S_{sw}(f)$  is the swell spectrum and  $S_w(f)$  is the wind sea spectrum.

The Torsethaugen two-peak spectrum applied herein was established primarily for one location (Statfjord, the Northern North Sea) but in qualitative terms is expected to be of much broader validity, and is currently used by the Norwegian industry for locations exposed to North Atlantic swell. The spectrum is an average wave spectrum derived by introducing various empirical factors, and therefore it should not be used uncritically for other locations. An attractive feature of the Torsethaugen spectrum is that only limited information about the sea-state is required as the spectrum is completely defined given the significant wave height and spectral peak period. The model splits the energy into a swell component and wind-sea component, using a modified JONSWAP spectrum for both peaks. It is noticed that even though including contribution from wind sea and swell the Torsethaugen spectrum does not necessarily need to have two *pronounced* peaks.

In the Torsethaugen model, each sea state is classified as *swell dominated* sea or *wind dominated* sea according to the criterion:

$$\begin{array}{ll} \text{swell} & \text{if } T_p > T_f \\ \text{windsea} & \text{if } T_p \leq T_f \end{array} \quad \text{where} \quad T_f = a_f H_{mo}^{1/3} \quad (5)$$

where  $T_p$  is the peak period, and  $a_f = 6.6$  is adopted from the JONSWAP experiment [9]. If  $T_p \leq T_f$ , the local wind-sea dominates the spectral peak, if  $T_p > T_f$  the swell dominates the spectral peak.

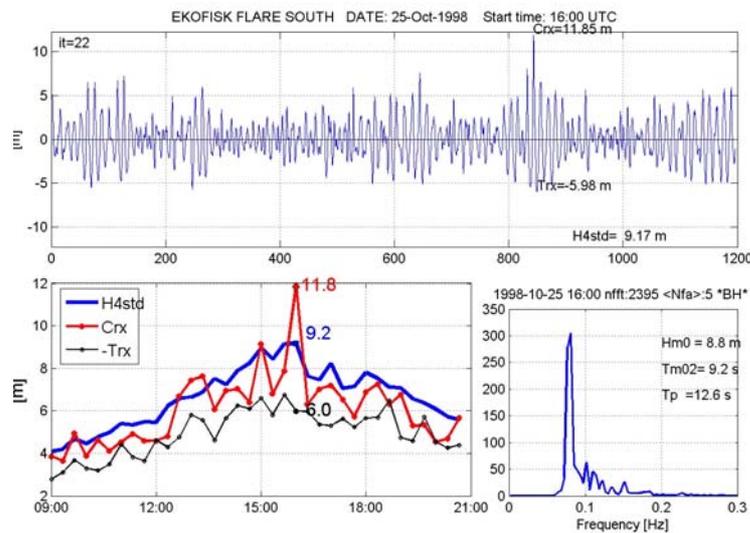
The statistical results presented herein are based on 350 simulations of a 1024 sec timeseries at 4Hz for the long-crested sea. A 1024 sec timeseries includes approximately 90-120 wave cycles. The chosen number of simulations gives reasonably stable results [3]. Typically the analyzed parameters evaluated from the simulations have approximately constant values for number of simulations  $N > 250$ . The calculations are carried out for the Torsethaugen spectrum and JONSWAP assuming peak enhancement factor  $\gamma$  equal to 3.3 and 1.0 (Pierson-Moskowitz). Results for deep/intermediate water depth are reported herein (water depth 70m).

#### 4 Comparison of Wave Characteristics

Different definitions of freak waves are proposed in the literature. Often used as a characteristic is that the factor  $H_{max}/H_s > 2$  (maximum crest to trough wave height factor). A ratio larger than 2 is seldom to be found in measured data, especially when measured by buoys due to the typical lack of skewness in these data [12, 13]. But this factor may not always be sufficient for an operational definition of an extreme or freak wave. Another commonly advocated definition of freak waves is a criterion based on the factor  $C_{max}/H_s$ , e.g. as suggested by Haver and Andersen [11] that  $C_{max}/H_s > 1.2$  within a 20-minute sea elevation time series. Tomita and Kawamura [18] suggest that both a wave height and a crest height criterion be simultaneously fulfilled, with the height factor

higher than 2 and the crest factor higher than 1.3. Guedes Soares et al.[7, 8] argue that use of the height factor and the crest factor is not sufficient.

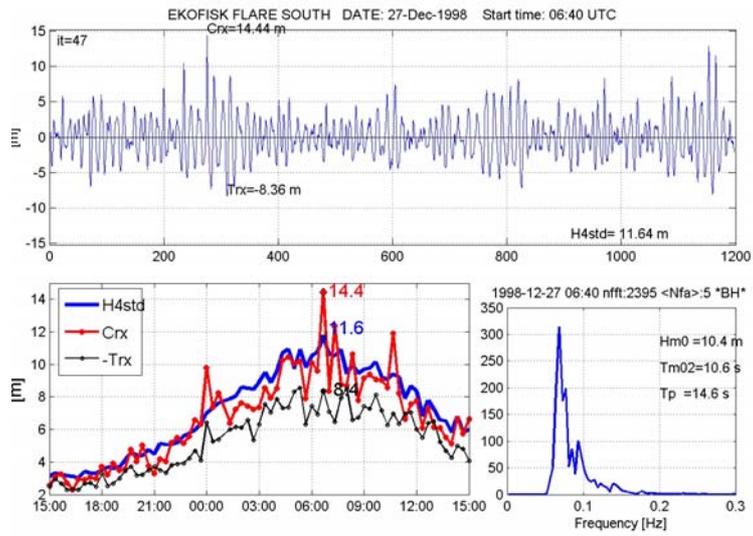
All wave records chosen for the present study include an event  $c/H_s > 1.2$  and are shown in Figures 2-8. In each figure the top panel represents the 20 minutes time series sampled at 2Hz including the crest event analysed. Lower left panel shows the time history of significant wave height, maximum crest and trough in each 20minutes records during the storm. Lower right panel shows the frequency spectrum from the time series shown in top panel, using Blackman-Harris windowing and Fourier analysis on all data (nfft=2395, nb of samples), thereafter averaging the spectrum over 5 frequency bins (Nfa=5).



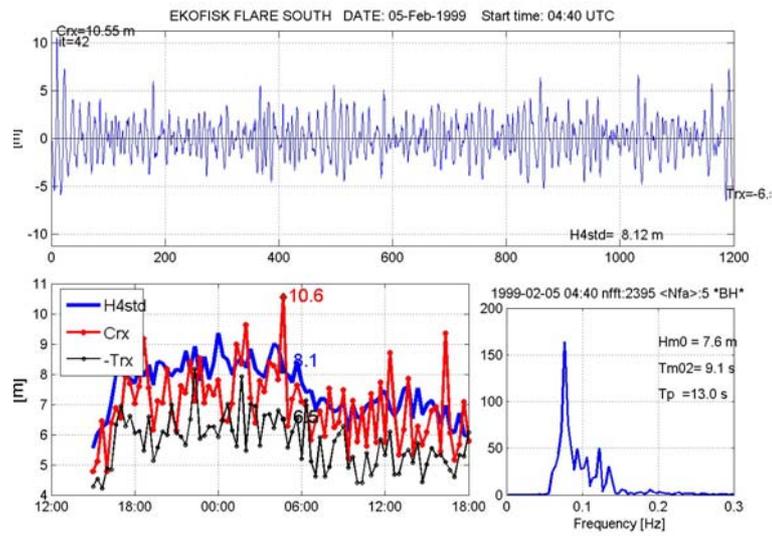
**Fig. 2** Case 1: Measurements from laser at Flare South at Ekofisk during 25. October 1998. Lower left panel: Blue line: significant wave height using  $H_{4std}$ , red line: max crest height (Crx) in each 20 minute record, black line: inverse of deepest trough (Trx) measured in each 20min record.  $C_{max}/H_{4std} = 1.29$  at 16:00 UTC

As seen in these figures the extreme events appear at different times of the storm histories, before, at, and after the significant wave height culmination (referred to here as part of storm with the highest  $H_s$ ). Further, as shown in Table 2, by applying the Torsethaugen criterion (Eq.(5)) only the Draupner wave record (sea state 6,  $T_p=16.7s$ ) represents clearly swell dominated sea. The sea state measured in case 2 (27 December 1998, 06:40 UTC) with  $T_p=14.6s$ , is very slightly swell dominated ( $T_p > T_f$ ) when  $H_{m0}$  is used in calculation of  $T_f$  and wind dominated when  $H_{4std}$  is used. The relation between  $T_p$  and

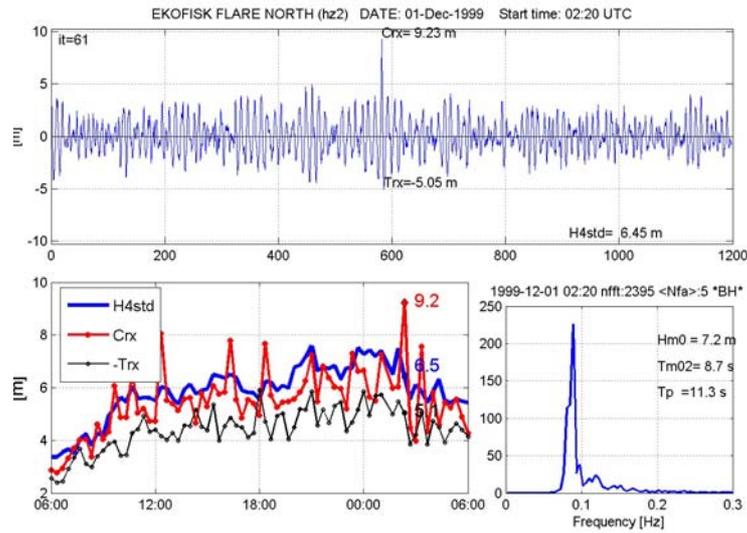
$T_f$  calculated from the spectra in the other cases (1, 3, 4, 5 and 7) indicates that the sea state is wind dominated following the Thorsethaugen criterion.



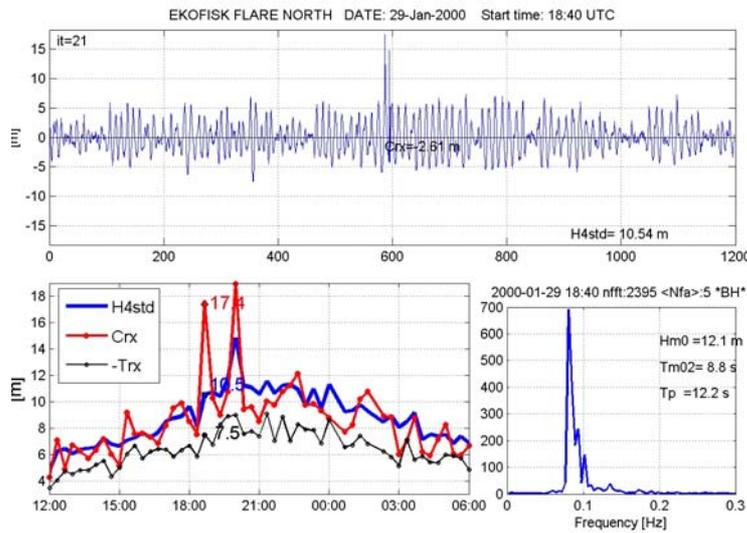
**Fig.3** Case 2: 27 December 1998 storm .  $C_{max}/H_{4std} = 1.24$  at 06:40 UTC.



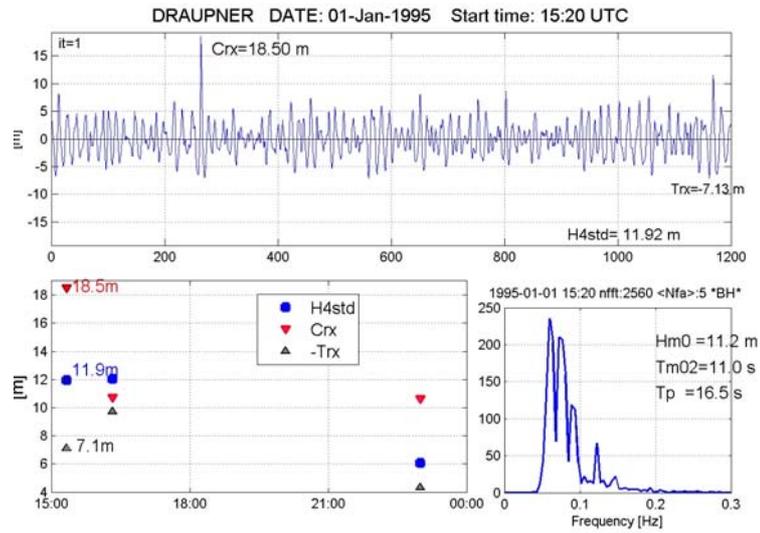
**Fig.4** Case 3: 5-6 February 1999 storm.  $C_{max}/H_{4std} = 1.31$  at 04:40 UTC the 6<sup>th</sup>.



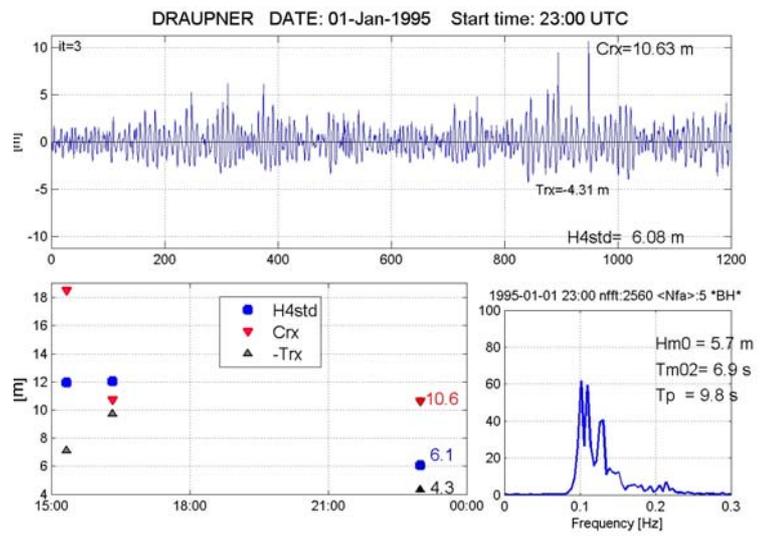
**Fig.5** Case 4: 30. November – 1. December 1999 storm. Flare North measurements with  $C_{max}/H_{4std} = 1.43$  at 02:20 UTC the 1<sup>st</sup>.



**Fig. 6** Case 5: Flare North at Ekofisk, 29-30 January 2000.  $C_{max}/H_{4std} = 1.65$  at 18:40 UTC the 29<sup>th</sup>.



**Fig. 7** Case 6: The Draupner “New year wave” recorded during the 1 Jan. 1995 storm, at 15:20UTC. Lower left panel shows the crest in detail.  $C_{max}/H_{4std} = 1.55$



**Fig. 8** Case 7: Second case from the Draupner platform on 1 Jan. 1995 storm, 23:00UTC. ( $C_{max}/H_{4std} = 1.75$ ).

As expected (see Table 1) different crest to height ratios ( $C_{max}/H_s$ ) are obtained using either  $H_{4std}$  or  $H_{m0}$ , and the difference between the ratios is significant for some wave records (see Table 2). Use of  $H_{4std}$  or  $H_{m0}$  may decide whether an event is classified as a freak event or not. Herein  $H_{4std}$  has been adopted because further discussions on which standard spectral analysis method to use is outside the scope of this paper.

**Table 2. Sea surface characteristics.**

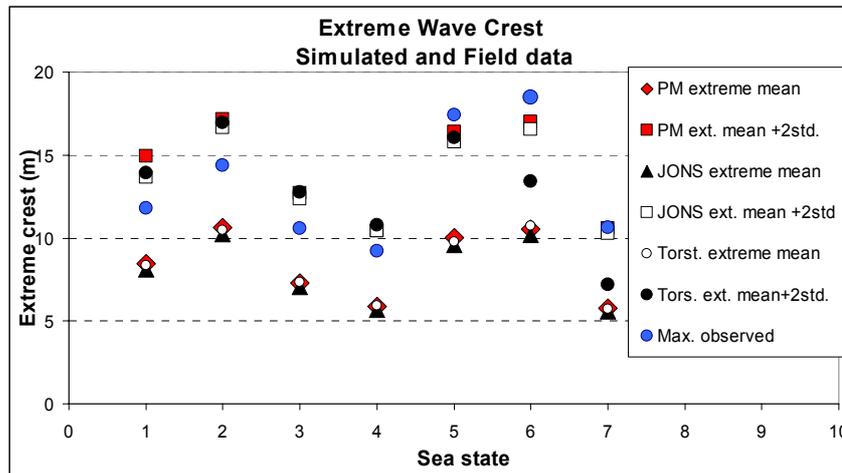
Sea state	$T_p$ (s)	$T_f^*$ (s)	$T_f^{**}$ (s)	Field data			Simulations – PM*		
				$C_{max}$ (m)	$C_{max}/H_{4std}$	$C_{max}/H_{m0}$	$E[C_{max}]$	$\sigma_{C_{max}}$ (m)	$E[C_{max}]/H_{4std}$
1	12.6	13.8	13.6	11.8	1.29	1.34	8.47	2.91	0.92
2-w/sw d.	14.6	14.9	14.4	14.4	1.24	1.38	10.62	3.26	0.91
3	13.0	13.3	13.0	10.6	1.31	1.39	7.31	2.71	0.90
4	11.3	12.3	12.7	9.20	1.43	1.28	5.88	2.43	0.91
5	12.2	14.5	15.1	17.4	1.65	1.44	10.04	3.17	0.95
6-swell d.	16.7	15.1	14.8	18.50	1.55	1.65	10.53	3.25	0.88
7	9.8	12.0	11.8	10.63	1.75	1.86	5.76	2.20	0.95

\*  $H_{4std}$ , \*\*  $H_{m0}$

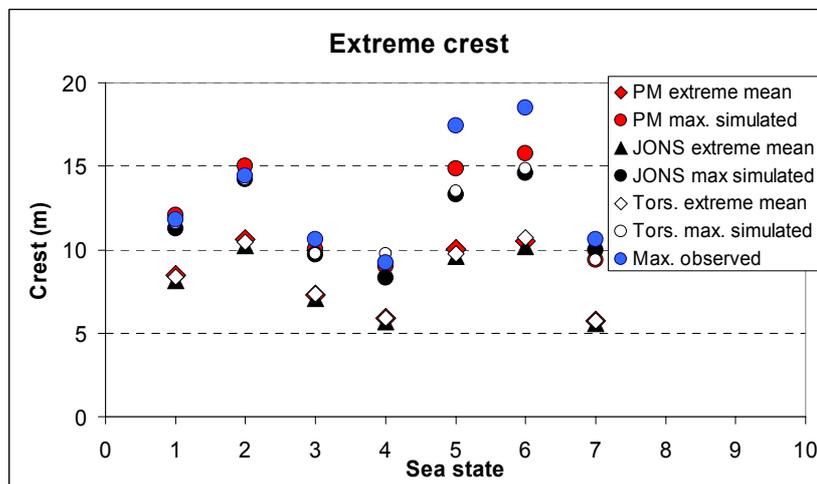
The second order simulations have been carried out using water depth of 70m, assumption of long-crested sea and  $H_{4std}$  and  $T_p$  as an input.  $T_p$  will depend on the averaging method used in the spectral calculations. In Table 2 results from simulations assuming a Pierson-Moskowitz (PM) spectrum are presented. Figs. 9 and 10 show results from simulations using all 3 types of spectral shapes (PM, JONSWAP and Thorsethaugen). In Fig.9 the mean and mean + 2\*std of simulated extreme crests are compared with observations, while in Fig. 10 the mean and the maximum values of simulated maximum crests are compared with the maximum observed crests.

The JONSWAP spectrum with the factor  $\gamma$  equal to 3.3 gives lower mean extreme crest in comparison to the Pierson-Moskowitz and Torsethaugen spectrum in all cases. This can be attributed, in average, to larger spectral width for the two latter spectra, than the JONSWAP spectrum for the sea states considered, see also [4]. Further, we can see that the Torsethaugen spectrum increases slightly the extreme crests in average for the Draupner sea state 6, but, however, reduces the standard deviation. For the PM spectrum the mean extreme crest obtained from the 2<sup>nd</sup> order time domain simulations is up to 43% lower compared to the maximum observed crest. For the last 3 cases ( 5 (January 2000), 6 (Draupner 1995, 15:20UTC) and 7 (Draupner 1995, 23:00UTC)), the observed maximum crest is outside the interval range of the simulated mean of extreme crests plus two standard deviations of the extreme crest distribution, particularly for the higher sea states 5 and 6 (10.5m and 11.9m, compared to 6.1m in case 7). This confirms

the earlier findings presented in the literature; the freak wave observed at Draupner cannot adequately

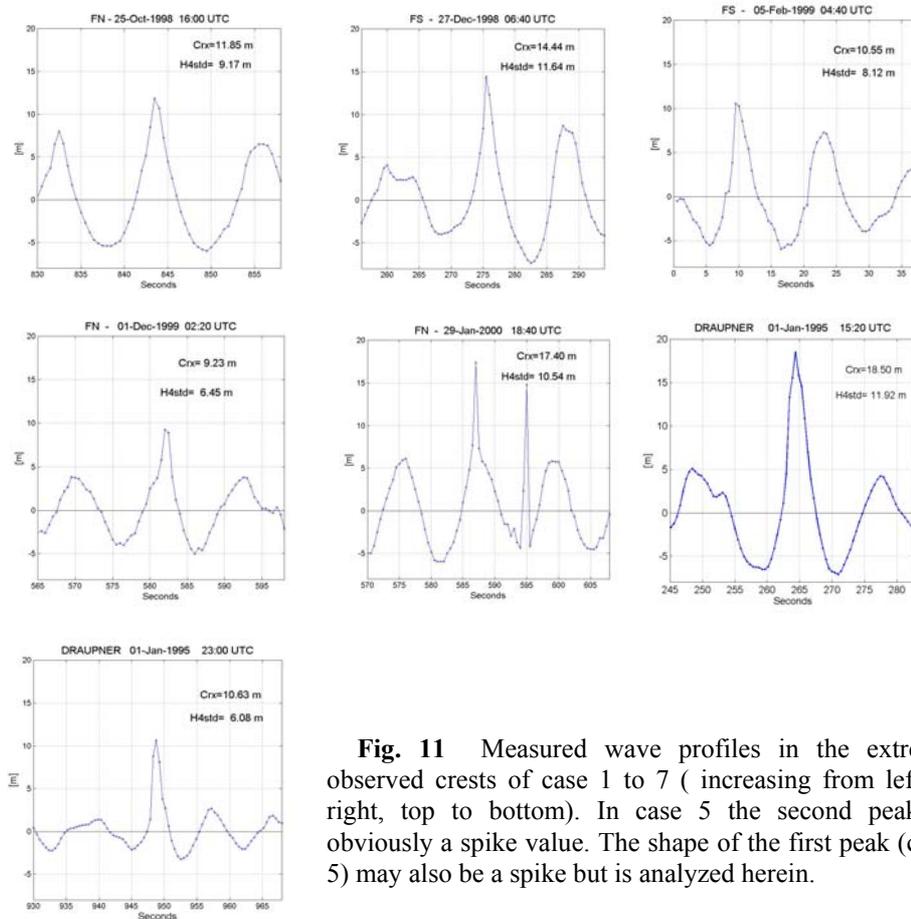


**Fig. 9** Extreme wave crests in the 6 storm cases. Blue filled circles are observations. For simulations assuming Pierson-Moskowitz, JONSWAP and Thorsethaugen spectral shapes: given here are mean of maximum crests (points are all below observations) and its value + twice the standard deviation (see legend for symbol and color).



**Fig. 10** As for Fig. 9, but simulation results are shown with mean and maximum values of maximum crest.

be accounted for by the 2<sup>nd</sup> order model. Note that the wave crest in the case 5 can be put in doubt due to the form (Fig. 11) of the wave behind the crest. However, for the less extreme events in cases 1 to 4 where  $C_{max}/H_s < 1.45$ , the 2<sup>nd</sup> order model ‘captures’ the observed maximum wave crest, thus the maximum observed crest is close to the crest extreme mean plus two standard deviations, see also [3].

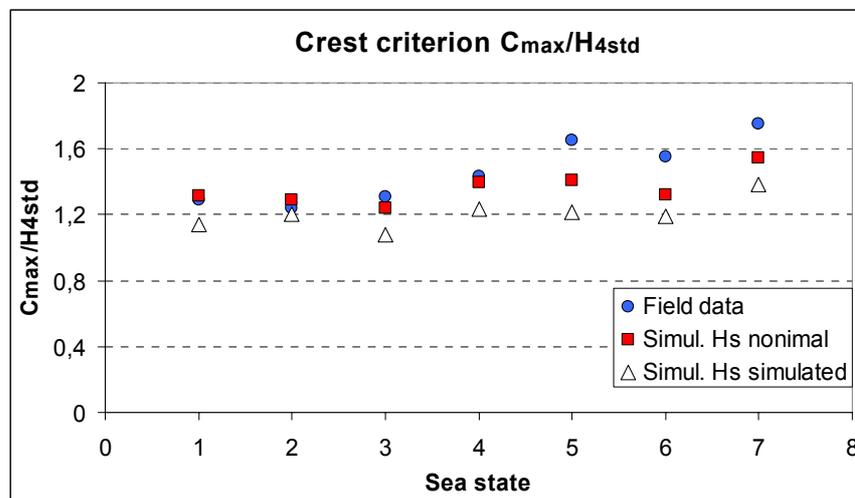


**Fig. 11** Measured wave profiles in the extreme observed crests of case 1 to 7 ( increasing from left to right, top to bottom). In case 5 the second peak is obviously a spike value. The shape of the first peak (case 5) may also be a spike but is analyzed herein.

The simulation results reported in Figs. 9 and 10 are based on the nominal (observed) significant wave height,  $H_{s,nom}$ . However, as pointed out by Bitner-Gregersen and Hagen [3] for a sample of 17 minutes time series there is a scatter in the spectral variance caused by sampling variability, which is accounted for in the simulations through random spectral amplitudes. For time series of 17 minutes duration, the coefficient of variation for significant wave height for a sample of realizations is in the range

5-7% (Olagnon & Magnusson [15] also showed  $H_{m0}$  calculated from simulations varied with up to 9%, in the mean 6%).

A high value of  $C_{max}/H_{s,nom}$  may occur in a sea state in which also the simulated significant wave height is high ( $H_{s,sim} = 4 \cdot \text{standard deviation of } 2048 \text{ simulated wave elevation values}$ ). In this case,  $C_{max}/H_{s,sim}$  would be lower than  $C_{max}/H_{s,nom}$ . On the other side, a high crest observed in a 3 hour sea state may very well occur in a part of the sea state where the 20 minutes averaged significant wave height is substantially higher than the 3 hour averaged  $H_s$ , making the factor  $C_{max}/H_{s,nom}$  low. In Fig. 10, the maximum simulated and observed wave crests are shown while Fig. 12 illustrates the difference between  $C_{max}/H_{s,nom}$  and  $C_{max}/H_{s,sim}$  for the PM spectrum. As can be observed, there is a clear difference, and this aspect should be kept in mind when evaluating freak criteria based on  $C_{max}/H_s$  or  $H_{max}/H_s$  ratios.



**Fig. 12** Wave crest factor for nominal and simulated significant wave height using PM spectral shape.

## 5 Summary of Discussion

Cases analyzed herein show that the ratio  $C_{max}/H_s$  may vary significantly depending upon whether the significant wave height is calculated from the time series  $H_{4std}$  (4 times standard deviation) or from the zero-spectral moment  $H_{m0}$ . Which formulae is used may influence on deciding whether an event is classified as a freak wave or not. It is recommended to use both significant wave estimates with care, and investigate them further if significant difference between them is observed.

Cases 1 to 4 with the less extreme waves ( $C_{max}/H_s < 1.45$ ) are well ‘captured’ by the 2<sup>nd</sup> order wave model. By capture it is meant here that the observed maximum crest is close to the simulated mean of extreme crests plus two standard deviations of the extreme crest distribution. This could be utilized in design by calibrating the extreme mean crest calculated by the 2<sup>nd</sup> order wave model. There is though no assurance that the observations have captured the most extreme waves in the area around Ekofisk due to changing profiles as waves evolve [13].

When  $C_{max}/H_s > 1.45$ , particularly for higher sea states with  $H_s > 10.0\text{m}$ , the observed maximum crest is outside the interval range of the simulated mean of extreme crests plus two standard deviations for the records characterized. Using the Thorsethaugen criterion [19] to define the sea state to be wind sea or swell, we find that two of these cases have been recorded in wind dominated sea (January 2000 storm, Draupner sea state at 23:00UTC) and the third one, the Draupner wave 1. January 1995 at 15:20UTC, in a swell dominated sea. Simulations of the Draupner wave assuming the Thorsethaugen spectral shape gives slightly higher mean values of the extreme crests as compared to PM or JONSWAP shapes.

In the first four cases, JONSWAP shapes give lower mean values, and PM shapes give highest extremes. Differences are though within decimetres.

The above leads to the conclusion that spectral shapes do influence results but a question is how significant these differences are. Further investigations are required to reach a firm conclusion.

It must be noted that of the 7 cases considered, the first 4 high crests occurred at end of the culmination period, when wind has relaxed to slightly lower speed, and wind direction is in a veering situation. This indicates that the sea state might be bi-directional at the event. Case 5, which is probably a spike, occurs in a strong growth phase of the storm (in which sea spray is highly probable). Cases 6 and 7 are a bit more difficult to define weatherwise (wavewise). Wind was around 20m/s all afternoon in the Northern North Sea, but analysis of weather maps also indicate the high crest events at both 15 and 23 occur in a slackening situation in the wind field as the wind direction is veering slowly towards North. Again one might find a spectrum with large spread or bi-directionality in these cases.

The present analysis is limited to long-crested sea. Further investigations including directional effects are called for.

## Acknowledgement

The work presented was performed partially within the EU - Project “*Safety and Reliability of Industrial Products, Systems and Structures*” (SAFERELNET), which is described in <http://mar.ist.utl.pt/saferelnet/> and is funded partially by the European Com-

mission under the contract number G1RT-CT2001-05051 of the programme “Competitive Sustainable Growth”.

## References

1. Birknes, J. and Bitner-Gregersen, E.M.: Non-linearity of the Second-order Wave Model for Directional Two-Peak Spectra. Proc. ISOPE'2003 Conf. Hawaii. (2003).
2. Bitner-Gregersen, E. M.: Sea state duration and probability of occurrence of a freak crest. Proc. OMAE'2003 Conf., Cancun, Mexico (2003).
3. Bitner-Gregersen, E.M. and Hagen, Ø.: Effects of Two-Peak Spectra on Wave Crest Statistics. Proc. OMAE'2003 Conf., Cancun, Mexico (2003).
4. Bitner-Gregersen, E. M., and Hage, Ø.: Freak Waves in the Second Order Wave Model. OMAE'2004 Proc., Vancouver, Canada (2004).
5. Ersdal, G. and A. Kvitrud,: Green water incidents on Norwegian production ships. Proceedings of ISOPE'2000 (2000).
6. Forristall, G. Z.: Wave Crests Distributions: Observations and Second-Order Theory. J. Physical Oceanography, vol.30. No.8. pp.1931-1943. (2000)
7. Guedes Soares, C., Cherneva, Z., and Antao, E.M., “Characteristics of Abnormal Waves in North Sea Storm Sea States. Accepted for publication in J. Applied Ocean Research (2004a).
8. Guedes Soares, C., Cherneva, Z., and Antao, E.M.: Abnormal Waves during Hurricane Camille. Accepted for publication in J. Geophysical Research (2004b).
9. Hasselmann, K. and Co-authors: Measurements of Wind-wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP). Dtsch. Hydrogr. Z.. Suppl. A. Vol.8. (1973).
10. Hagen, Ø.: Statistics for the Draupner January 1995 Freak Wave Event. Proc. OMAE-2002 Conference, Oslo, Norway (2000).
11. Haver, S. and Andersen O. J.: Freak Waves. “Rare Realizations of a Typical Population or Typical Realizations of a Rare Population.”. ISOPE' 2000, Seattle (2000).
12. Longuet-Higgins, M.S.: Eulerian and Lagrangian aspects of surface waves. J. Fluid Mech. 173, 683-707, (1986).
13. Magnusson, A. K., M. A. Donelan and W. M. Drennan: “On estimating extremes in an evolving wave field.” *Coastal eng.* **36**, pp 147-163 (1999).
14. Magnusson, A. K., Bitner-Gregersen, E.M. and Nieto Borge, J.C.: Analysis of Extreme Waves in the Maxwave Database. WMO Proc. Geneva (2003).
15. Olagnon, M, and A. K. Magnusson, 2004: “*Sensitivity study of sea state parameters in correlation to extreme wave occurrences*”. In proceedings of 14<sup>th</sup> international Offshore and Polar Engineering conf., ISOPE 3, (2004).
16. Pierson, W.J. and Moskowitz, L.: A proposed Spectral Form for Fully developed Wind Seas based on the Similarity Theory of t.A.A. Kitaigorodskii. J. Geoph. Res. Vol 69, pp 5181-5190 (1964).
17. Prevosto, M. and Bouffandeau, B.: Probability of Occurrence of a “Giant” Wave Crest. Proc. OMAE-2002 Conference, Oslo, Norway (2002).

18. Tomina, H. and Kawamura, T.: Statistical Analysis and Inference from the In-Situ Data of the Sea of Japan with Reference to Abnormal and/or Freak Waves. Proc. ISOPE'2000 Conf., Seattle, USA (2000).
19. Torsethaugen, K.: Model for Double Peaked Wave Spectrum. SINTEF Civil and Environmental Engineering, Rep. No. STF22 A96204, Trondheim, Norway (1996).