Some cases of observed rogue waves and an attempt to characterize their occurrence conditions

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Abstract. There is no consensus at present as to whether extreme waves are “normal” extremes in an homogeneous population of waves, or the results of totally different generation mechanisms, such as for instance non linear interaction and phase locking of wave trains.

In a first stage of the present paper, we analyse a few selected extreme waves measured in the North Sea, and we verify, according to several criteria, that these waves can be classified as Rogue Waves according to the criteria commonly accepted. In addition, the occurrence of a very deep trough in front of the wave is verified by examination of the reconstructed instantaneous space profiles of the water surface at several time-steps before the maximum crest.

In a second stage, the sea states where the selected extreme waves occurred are studied and characterized in terms of spectral bandwidth and multiple peakedness, of steepness, of non linearity, of wind conditions, and of the characteristics of the storm that contains them. These sea states are then compared with the other sea states of similar $H_s$ where no rogue wave could be observed, with the intent to find some differences or trends that could then be used as forewarning signs of an increased risk of occurrence of rogue waves. Unfortunately, most of the differences are not significant enough to make a decisive step forward in the forecast of risks of rogue waves.

Lastly, the individual rogue waves that were identified are analysed, both in the time domain and from the reconstructed shape that can be calculated in space. Special attention is given to the individual wave steepness and to its vertical and horizontal asymmetry. These parameters are compared to the same ones for “normal” maximum waves in other sea states.
Nomenclature

\( H_s \) Significant wave height
\( T_z \) Mean period estimated with \( \sqrt{\frac{m}{m+2}} \)
\( C_s \) Sea state steepness calculated using \( \frac{H}{1.56T_z} \)
\( H \) Down-zero-crossing wave height
\( A_C \) Crest height defined as the maximum height observed between an up-zero-crossing and the following downcrossing
\( T \) Wave period (by zero downcrossing counting)
\( T' \) Crest front period, see [3] for details
\( T'' \) Crest rear period, see [3] for details
\( L \) Wave length
\( L' \) Crest front wave length, see [3] for details
\( L'' \) Crest rear wave length, see [3] for details
\( \mu_h \) Wave horizontal asymmetry, or height asymmetry, \( \frac{A_C}{H} \)
\( \mu_w \) Crest vertical asymmetry, or front/back asymmetry, in space \( \frac{L'}{L''} \)
\( \mu_v \) Crest vertical asymmetry, or front/back asymmetry, in time \( \frac{T'}{T''} \)
\( S_t \) Individual wave steepness by space domain analysis, \( \frac{H}{L} \)
\( S_t \) Individual wave steepness by time domain analysis, \( \frac{H}{T} \)

Introduction

There is no lack of evidence that extreme and dangerous waves exist: their gigantic size has been testified by many shipmasters’ reports and their dangerousness has been proven by damages on ships and offshore structures, some examples of which are described in Ersdal & Kvitrud (1999) [1] or Kjeldsen (1997) [4].

However, the problem as to whether those waves are normal waves or abnormal ones in a statistical sense is still unsolved. The present paper intends to reach a better understanding of those waves by considering the extreme waves of the Frigg in situ data set, see [5] for details.

The first question raised in this paper is whether the waves selected in the Frigg data set are of the same kind as the extreme waves reported by metocean engineers and shipmasters.

The problem of whether those waves can be called “rogue” (or “freak”) is discussed in parts two and three. If they were “freak” or “rogue” waves, it should be possible to find characteristics that distinguish them from the “conventional” extreme waves. Two characterics are studied: the individual shape of the individual waves, especially wave asymmetry and wave steepness, as presented in the second part; and the conditions in which those extreme waves occur, analysed in the last part.
1 Are we talking about the same waves?

1.1 Selection of extreme waves

Extreme waves analysed in this study have been selected according to two criteria, further named \( Ch \) and \( Cc \).

\[
Ch \equiv \frac{H}{H_s} > 2 \quad \text{and} \quad Cc \equiv \frac{A_c}{H_s} > R_0
\]

The value 1.25 has been chosen for \( R_0 \) so that the number of waves selected with \( Ch \) would be similar to that of the ones selected with \( Cc \). Examination of the dataset showed that the commonly used value of 1.1 was too frequently overpassed for a study that intends to deal with rare extremes. Only sea states with \( H_s \) larger than 2 m were considered.

We define a maximal wave as the wave corresponding to the highest crest of a given sea state. The set of maximal waves was then searched for extreme waves according to criteria (1). The numbers of waves selected in each set are presented in table 1.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frigg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total ( H_s &gt; 2m )</td>
</tr>
<tr>
<td></td>
<td>1,600,000</td>
</tr>
</tbody>
</table>

Table 1. Description of the selected waves

Two sets of sea states are considered. The first one corresponds to all sea states with \( H_s > 2 \) m and the second one to sea states for which \( H_s \) is larger than 2 m and the maximal wave crest higher than 5 m. Proportions of extreme waves are presented on table 2.

<table>
<thead>
<tr>
<th>Sea state subset</th>
<th># Maximal waves</th>
<th># Extreme waves</th>
<th>% Extreme waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_s &gt; 2m )</td>
<td>9858</td>
<td>79</td>
<td>74</td>
</tr>
<tr>
<td>( H_s &gt; 2m ) &amp; ( Ac &gt; 5m )</td>
<td>780</td>
<td>22</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 2. Extreme waves among maximal waves

Extreme waves have then been selected according to the criteria (1) commonly used to identify ”freak” waves, but no justification of abnormality was
made so far, so we will keep to naming them extreme waves.
A peculiarity of abnormal extreme waves for shipmasters is the “hole in the
sea” that can be observed ahead of the wave. We investigate in the next part
whether such a hole could have been observed ahead of the waves that we se-
lected.

1.2 Is there a “hole in the sea” ahead of the selected waves?

The analysis of the water surface elevation time history around the selected
waves leads to the conclusion that the troughs ahead of high waves are benign.
Observations from ships’ bridges are however mostly relevant to spatial shapes
of waves. To get an estimation of the wave shape in space, the following method
is applied:

- The Fourier transform is applied to the time history, converting it into the
  frequency domain.
- A change of variables is performed to turn frequency into wavenumber, by
  use of the dispersion relationship.
- The values are multiplied by the appropriate complex phase to shift to the
  instant of interest.
- The inverse Fourier transform is then applied, thus providing the space
  shape.

It should be noted that with this method, waves are assumed to be all free waves
propagating in a single direction.

Figure 1 presents an extreme wave recorded by the Frigg radar on 2 February
1988 in a sea state when Hs was 6.7m. Instantaneous space wave profiles have
been computed every 0.5 s. The 40 wave profiles from T-20s to T, where T is
the time at which the extreme crest is measured by the sensor, are presented on
the top figure. The figure below shows the 20 profiles from T to T+10s.

It is interesting to note that the trough at time T is indeed not outstanding and
that the wave crest-trough dissymetry at that time is consequently very large.
Such features are commonly observed with measurements from fixed platforms.
If we consider now the wave profile at T-8s (yellow line), the crest is not so high
but the trough, around 8m, is very deep.

If a sensor had been placed 30 m ahead (in the wave propagation direction) of
the Frigg radar, a “hole in the sea” would have been recorded, but it would not
necessarily have been matched with a maximal crest. The instantaneous profile
about 5 seconds after T also shows a deep trough. Most all extreme waves
relative to Frigg data present similar profiles as the one presented above, i.e.
the peculiarities described by shipmasters in reports of “rogue waves”. Out of
46 extreme waves, 43 were also extremal in the sense of Podgórski et al (2000)
[6], i.e. the crest was a maximum both in the time dimension and in the space
dimension. Every single one of them exhibited a much deeper trough, about 0.25
wave-length ahead of the maximal crest in space and 0.75 period ahead in time,
with respect to the point measurement time-history.
Fig. 1. Instantaneous space profiles

Fig. 2. Preceding trough versus crest
Figure 2 shows the difference between the trough depths corresponding to the maximal waves in the time-history (blue squares) and the troughs at their deepest in space and time ahead of these waves (red circles). Despite the fact that there might be a slight increase in the trough depth due to the assumptions used for estimation of the waves space shapes, there are many good reasons to believe that our selected extreme waves are of the same nature as the ones that were actually observed and identified as damaging giants. Whether these selected waves are normal extremes is discussed in the next sections.

2 What do individual extreme waves look like?

If those selected waves are abnormal, it should be possible to find features to distinguish them from other normal large waves. To check if it is the case, parameters relative to individual wave shapes have been chosen and their distributions have been compared for different subsets.

The subset of “conventional waves” (780 waves) corresponds to the “maximal waves” of each sea state for which the maximal crest is larger than 5m. The subset of extreme waves corresponds to the “conventional waves” identified as “extreme waves” with criteria of formula 1 (46 waves).

Parameters investigated are:

1. Wave horizontal asymmetry, or height asymmetry $\mu_h = \frac{A}{H}$
2. Crest vertical asymmetry, or front/back asymmetry, in space $\mu_{vs} = \frac{L}{T}$ and in time $\mu_{vt} = \frac{T}{2T}$
3. Wave steepness in space $\frac{H}{L}$ and in time $\frac{H}{1.56T^2}$
4. Crest front steepness in space $\frac{A_c}{L}$ and in time $\frac{A_c}{1.56(2T)^2}$

Parameters in space have been estimated from the reconstructed shape at the instant of the crest. To compare distributions, a Kolmogorov test is used to test hypothesis $H_0: F_T(x) = F(x)$ against $H_1: F_T(x) \neq F(x)$. $F_T(x)$ is said to be significantly different from $F(x)$ with risk $\alpha$ if the statistic $D_n = \sup_{x} |F_T(x) - F(x)|$ is higher than a value $\theta$, with $P(D_n > \theta) = \alpha$. The risk value used in the following of this paper is 5%.

2.1 Wave asymmetry

Figure 3 shows a comparison of the crest front/back asymmetry distributions. A distinction is made between extreme waves selected with the different conditions $Ch : \frac{H}{L} > 2$, $Cc : \frac{H}{T} > R_5$ and $Ch \cap Cc : \frac{H}{T} > 2\sqrt{\frac{T}{2T}} > R_5$.

The subset of the 780 maximal waves is denoted by FT on the following figures. There is no significant difference between the crest vertical asymmetry distribution of all maximal waves and that relative to the selected extreme waves. A larger difference is observed for the extreme waves selected with $Cc$ are considered: values of the vertical crest asymmetry parameter tend to be smaller for
those extreme waves, $\mu_c < 1$ for 70% of them whereas $\mu_c < 1$ for only 50% of the maximal waves. Most of those extreme waves have thus a crest back period smaller than the front one. That result is unexpected but care has to be taken on the fact than it relies on only 35 waves and should be validated by an additional study not only on the crest period but on the trough to crest period. Significant

differences appear between maximal and extreme waves when considering wave height horizontal asymmetry parameter, see figure 4. The median of the maximal wave distribution equals 0.63 and the one relative to the extreme waves 0.68. Differences are most important when only the extreme waves selected with $C_C$ are considered and become non significant if the extreme waves are restricted to the ones selected with $Ch$.

2.2 Wave and crest steepness

Comparisons of the individual wave or crest steepnesses are presented on figures 5 and 6. Figure 5 shows differences between maximal and extreme waves in terms of individual wave steepnesses. Extreme waves are steeper than maximal ones, whatever criterion ($Ch$ or $C_C$) is used to select them. Results relative to crest front steepness are not so clear, see figure 6, crest front steepnesses relative to extreme waves are still larger than the ones relative to maximal waves but differences are much smaller and nearly not significant.

Differences have been found between extreme and maximal waves: larger height horizontal asymmetry, wave steepness more important but those differences are not always significant and depend on the criterion used to select the extreme waves. It is thus not possible to assess the abnormality of extreme waves from this analysis.
Horizontal asymetry Ac/H in space

Horizontal wave asymetry distribution for wave with crest max >5m

Fig. 4. Wave horizontal (height) asymetry

Steepness distribution for wave with crest max >5m

Steepness H/L in space

Steepness H/1.56T² in time

Fig. 5. Wave steepness

Crest front steepness distribution for wave with crest max >5m

Crest front steepness Ac/L in space

Crest front steepness Ac/1.56T² in time

Fig. 6. Crest front steepness
3 What are the prevailing sea conditions when they occur?

In order to check whether extreme waves are likely to occur in some special unusual conditions, we analyse several parameters describing the sea states where they were observed. For each of these parameters, we compare the distribution for sea states during which extreme waves have been detected (128 sea states) with the distribution relative to all sea states with $H_s > 2m$ (9850 sea states), called common marginal distribution.

3.1 Sea state significant height and steepness

Figure 7 shows a comparison of the $H_S$ distributions for Frigg data. The distribution relative to the sea states with extreme wave selected with $Cc$ exhibits the largest differences from the common marginal one. Period distributions are identical in the extreme and common marginal cases. Comparison of the steepness distributions leads to the same conclusions as the $H_s$ distributions: extreme waves occur when sea states are steeper than the average. This increase in steepness is evenly observed over $T_Z$ occurrences, and thus essentially the consequence of higher $H_s$.

![Fig. 7. Sea state Steepness](image)

3.2 Multi- or single-peak spectra

Double peaked sea states are identified by a modified version of the Guedes Soares criterion [2], for which details can be found in Van Iseghem et al. (2001)
For several $H_s$ classes, the occurrence probability of double peaks is calculated and used as a reference for the occurrence probability relative to the sea states where an extreme wave occurs. The percentage of double peaks detected for sea states with extreme waves is smaller than when considering all sea states, see figure 8. It can be noted that there is no double peaked sea state at all for the 10% 'most extreme' waves selected, as well with $Ch$ as with $Cc$, but that significance of this fact is low since only 1% of the sea states where a double peak was detected have $H_s$ higher than 3m. Yet one single wave coming at some significant angle from the direction of other waves, even the highest of the sea state, might not be sufficient to create a second peak in the spectrum.

![Figure 8. Occurrence of double peak spectra](image)

3.3 Strong winds

Wind distribution restricted to extreme wave cases is significantly different from the common marginal one. Wind speed is larger for extreme waves and the difference is at highest if we consider only the extremes waves selected with $Cc$. However, it may be noted that the largest values of wind speed do not correspond to the most extreme wave ratios.
3.4 Worsening sea conditions

Figure 10 shows the distribution of the three parameters $H_S - H_{S-2}$, $H_S - H_{S-1}$ and $H_S - H_{S+1}$, where $H_{S-1}$ means the $H_S$ of the previous sea state in the record history (3 hours earlier), and $H_{S+1}$ that of the following one. For 75% of the selected sea states, we have $H_S > H_S - 2$ and for 80% of the selected sea states, $H_S > H_S - 1$ whereas $H_S > H_S + 1$ occurs in half of the sea states. The probability of occurrence of extreme waves is thus slightly higher when sea conditions have been worsening in the previous hours.
Conclusion

It has been investigated whether “rogue waves” would be normal or abnormal. Characteristics of those waves have been proven to be consistent between measurements from a fixed platform and shipmasters’ reports. Especially, the horizontal height asymmetry is very large at the time when the extreme wave occurs; but if the space wave profile at the instant a few seconds before is reconstructed, a deep trough akeen to a “hole in the sea” can be observed.

It is thus reasonable to assume that the selected extremes waves are of the same nature as the ones observed by mariners that have proven to be giant and dangerous.

A few hints have been provided to decide whether those waves are “normal” or not and tests have been made to try to distinguish them from the other common large waves. Some differences appear, relative to the individual wave shapes: larger horizontal wave height asymmetry, higher steepness, and to sea state conditions in which they occur: steeper sea states, worsening conditions. Nevertheless those differences are not significant enough to prove the belonging of those extreme waves to a different statistical population.

A recurrent problem with *in situ* data sets in the small number of identified extreme waves, which makes it difficult to conclude to any significant difference between extreme and common maximal waves.

We thus recommend that all available datasets be analysed in a similar fashion, and that further measurements be carried out in manners that would allow the identification of extreme waves, which is unfortunately not the case for many of the datasets currently recorded.

References