INVESTIGATING CONDITIONS FOR ROGUE WAVE EVENTS FROM SPECTRAL WAVE OBSERVATIONS AND MODELS

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1. INTRODUCTION

In recent years much attention has been drawn to the damage to large ships and offshore structures caused by rogue waves. The causes for the occurrence of waves of exceptional height or steepness, and the conditions under which they are most likely to occur, are active areas of research being pursued within the MAXWAVE project.

As part of the MAXWAVE project a database of ship accidents thought to be due to freak waves is being assembled. Spectral wave model hindcasts were performed in order to simulate as accurately as possible the sea-state conditions that occurred around the time and location of several cases selected from the database. These cases either reported freak wave damage to a ship, or resulted in structural damage to another construction in the vicinity. *In situ* observations of freak waves are indeed rare, and for the examples presented here we have high-resolution time series of observed wave height. These observations, with the wave model hindcasts, are used as a basis for the investigation of rogue waves.

A candidate for the development of rogue waves is the Benjamin-Feir instability. Some recent studies have attempted to link the development of rogue waves via the Benjamin-Feir instability with the nonlinear Schroedinger equation. Osborne *et al* (2000) performed numerical studies using families of JONSWAP power spectra as initial conditions. They found an increased occurrence of extreme wave heights for high values of gamma, the amount of peakedness in the spectrum. The conditions for the occurrence of this instability may hence be related to shape parameters of the wave energy spectrum that are calculable from wave model hindcasts and from high-resolution observations.

A further motivation to investigate the behaviour of JONSWAP gamma, is that current engineering practice favours the use of the JONSWAP spectrum to represent the frequency distribution of incoming waves when computing the action of these waves on offshore structures. A typical design criteria is to set gamma equal to two when describing the spectral shape of the hundred year return value of significant wave height in the North Atlantic.

Previous studies using wave model hindcasts and observations have not focused on the spectral shape parameters. In this paper we estimate the JONSWAP parameters from both observed and modelled spectra available during two storm events. In the first case we use observations from Ekofisk (56.5°N 2°E, central North Sea, see figure 1) taken during one of the MAXWAVE cases, and evaluate JONSWAP parameter values. In the second case we use observations from WS Polarfront (66°N 2°E, southern Norwegian Sea, see figure 1) during an extreme storm that occurred in November 2001, and here we compare observed spectra with spectra taken from WAM.

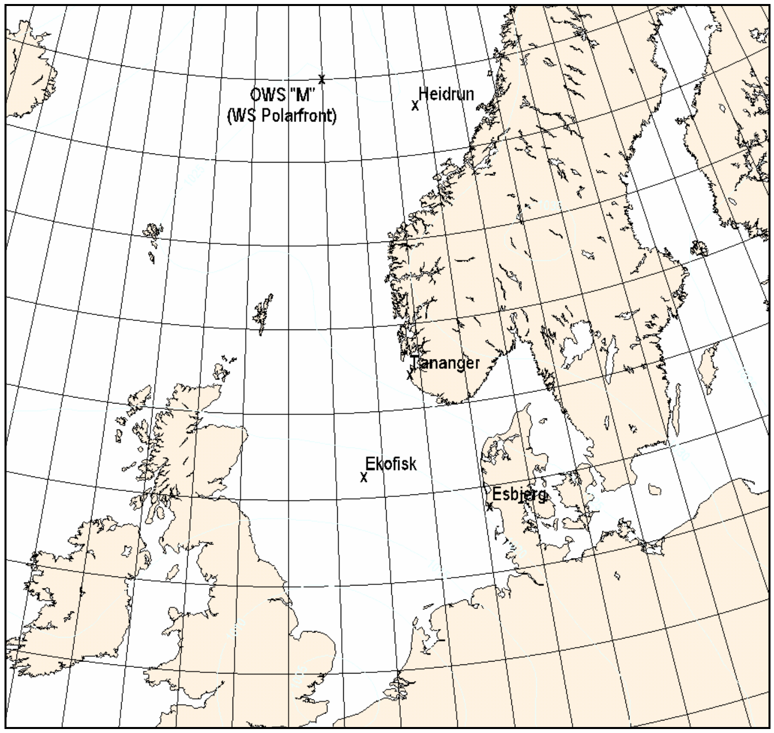

Figure 1: Chart of the North Sea and southern area of the Norwegian Sea.

2. FITTING SPECTRA TO PARAMETRIC SHAPES

The JONSWAP family of curves is given by

$$E_{JON}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left(-\frac{5}{4}\left(\frac{f}{f_m}\right)^{-4}\right) \gamma^{\exp\frac{-(f-f_m)^2}{2\sigma^2 f_m^2}}$$

where σ has a different value for frequencies smaller and larger than the peak frequency f_m. The JONSWAP curves have therefore five free parameters: α, f_m, γ, σ_a, σ_b which may be adjusted in order to fit to an observed wave energy spectrum (Hasselmann *et al*, 1973). The gamma variable represents the peak enhancement of the spectral peak of the wind sea, the sigma variable represents the narrowness of this peak, and alpha sets the level of the high frequency tail.

Several previous studies have fit JONSWAP parameters to observations of wave energy spectra. Standards in offshore design recommend values of γ, σ_a and σ_b to be 2, 0.07 and 0.09 (NORSOK, 1999). Donelan *et al* (1985) proposed another formula for the spectral shape with parameters dependent only on observed peak period and the wind speed. Their method also assumed a spectral fall-off proportional to f^{-4}, while the JONSWAP model assumes this to be proportional to f^{-5}. Recent analyses of spectral data (Prevosto et al, 1996) have shown that the tail behaviour is more close to an f^{-4} spectral fall off.

A variational method was developed to estimate JONSWAP parameter values from spectra, which imposes no external constraints on the JONSWAP shape function. A cost function defines the rms misfit between the observed and JONSWAP spectra. The functional form that computes E from the parameters: α, f_m, γ, σ_a, and σ_b (where the *a* and *b* refer to the left and right half-widths of the peak, see Hasselmann *et al*, 1973), is linearised and inverted in order to give the change in the value of each parameter due to a change in the value of the cost function, i.e. the adjoint operator of the above equation. Hence, the gradient of the cost function with respect to changes in the parameter values can be determined, and a gradient-search algorithm can be used to find the parameter values that minimise the cost function. This JONSWAP adjoint scheme is based on the same mathematical methodology employed in 4D-VAR at weather centres. An advantage of this method is that all of the observations of *E(f)* are used without imposing any external constraints.

3. CASE ONE: EKOFISK

The bulk carrier 'Stenfjell' arrived at Esbjerg harbour (west coast of Denmark) on the morning of 26 October 1998 with heavy weather damage to wheelhouse, accommodation and electrical installations, reported due to freak waves. The ship was sailing from Hamburg to Tananger (western Norway). No further information about the time and place of the event, and observed local conditions, is available from the Lloyd's database.

The storm waves that struck the Stenfjell in the morning of 26 October had been evolving across the North Sea. They were due to a strong northwesterly wind field, small in scale, but moving in the same direction of the wind field (from northern Scotland towards Hamburg, northern Germany) producing a so-called ‘moving fetch’. Wave profile measurements from 3 different sensors are available from the Ekofisk platform at 3.2°E, 56.5°N operated by *ConocoPhillips* (figure 1). These are sampled continuously and parameters are extracted every 20 minutes. Time series of significant wave height, maximum crest height and minimum trough (absolute value) are presented in figure 2 from the three sensors: WR (waverider buoy), FN (downward-looking laser at the northern end of the platform complex), and FS (downward-looking laser at the southern end of the platform complex). One can see that significant wave height (blue line) attained a maximum around 15 or 16 UTC, depending on what instrument is used. The waverider typically shows no difference between maximum crests and troughs, because of the typical wave-following behaviour of buoys, that smoothes the wave profiles. This does not happen with the laser measurements. Maximum crest height is recorded at FS (11.8m) in the record starting at 16:00, while FN has its highest value (11.7m) at 16:20. Both these crests have a ratio to Hs of 1.3, which is well above the criteria normally used as definition for rogue waves (1.1 or 1.2).

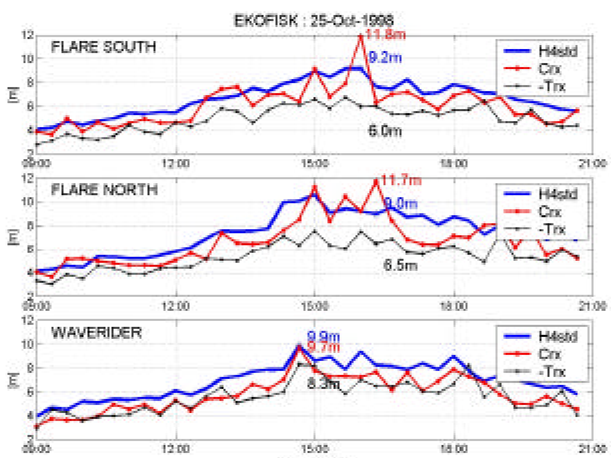

Figure 2: Wave height observations from Ekofisk during 25th October 1998

As one of the cases from MAXWAVE database, a wave model hindcast was performed using the Met Office UK waters wave model. Figure 3 (left panel) shows contours of Hs (significant wave height) and wind vectors over the model domain at 16:00 on 25/10/98.

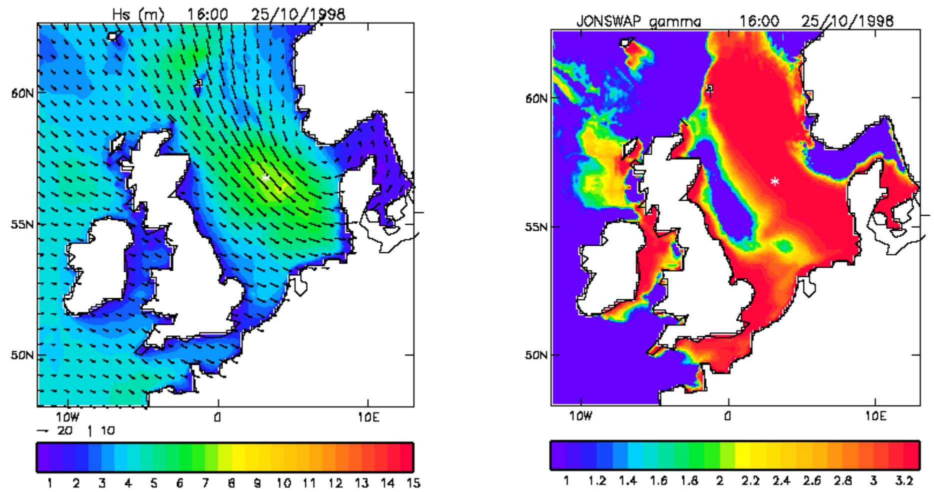

Figure 3: Left panel: contours of Hs and wind vectors from the Met Office UK waters wave model for 16:00, on 25/10/98. Location of Ekofisk platform is marked by an asterisk. Right panel: contours of JONSWAP gamma from the same model at the same time.

Being a 2nd-generation wave model, the modelled windsea in the hindcast is constrained to adopt a JONSWAP shape, and the gamma parameter can assume values between 1.0 and 3.3 as shown in the right panel of figure 3. It was found for this case, and others where there is strong local windsea growth, that gamma attains its maximum value over the region of interest. A necessary next step will be to run this hindcast using a 3rd-generation wave model that does not impose the JONSWAP shape on the windsea.

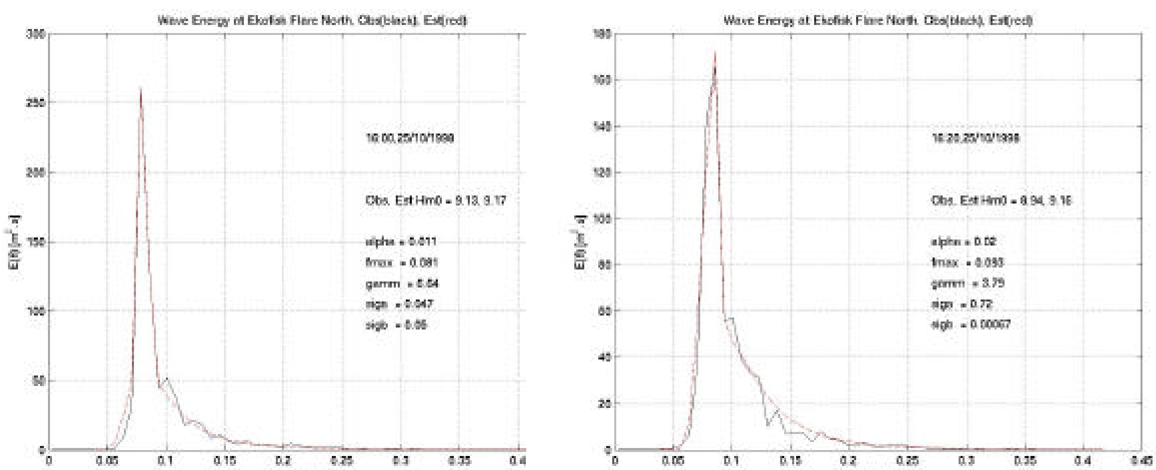

Figure 4: Energy spectrum from wave measurements at Ekofisk, from a laser at Flare North, on 25th October 1998, at 16:00 UTC (left) and 16:20 UTC (right). Dotted red line is the JONSWAP fit to the observed spectrum. At 16:00: γ=6.64, σ_a=0.047, σ_b=0.05. At 16:20: γ=3.79, σ_a=0.72, σ_b=0.0007

The wave energy spectrum around the maximum of the storm at Ekofisk was computed from the observed time series. JONSWAP parameters were then fitted to the spectrum. Figure 4 shows the observed spectra (black lines) evaluated from the wave profile recorded at FN at 16:00 UTC (left panel) and at 16:20 UTC (right panel).

The red lines show the fitted JONSWAP spectra. The peak is narrow in both cases, but much more pronounced at 16:00, when gamma is 6.64, than at 16:20 when gamma is 3.79. The ratio of maximum crest height to Hs is higher in the record starting at 16:20 (see figure 2), but the wave grouping is more pronounced in the preceding wave profile (16:00, not shown here) having a higher peakedness in the spectral shape. The highest wave crest measured in the 16:20 record occurs in the first 10 minutes of the record, within a large wave group. The second half of the record does not have a pronounced wave grouping, and has less gamma value. A high crest was measured at FS at 16:20 (see figure 2) with a ratio to Hs equa l to 1.3. The two sites (FN and FS) are 1050 meters apart, or approximately 4 to 5 wavelengths of the most energetic waves in this case. The shape of the waves change as they propagate (Magnusson *et al*, 1999) and the chance of measuring the wave group as it has its highest crest value is small. The observations at Ekofisk indicate a similarity with the results of Osborne *et al* (2000), that a high gamma value gives higher crests, but the observations also show how difficult it can be to perform a statistical analysis on such transcient phenomena as singular waves.

3. CASE TWO: POLARFRONT

During 10-11 November 2001, an extreme storm moved eastwards over the southern Norwegian Sea, producing a very high state that can be seen both in observations and wave model output. In this case both observed and modelled wave spectra where available. Figure 5 shows contours of Hs (from WAM) at the time of the storm passing over WS Polarfront (Ocean Weather Station "Mike").

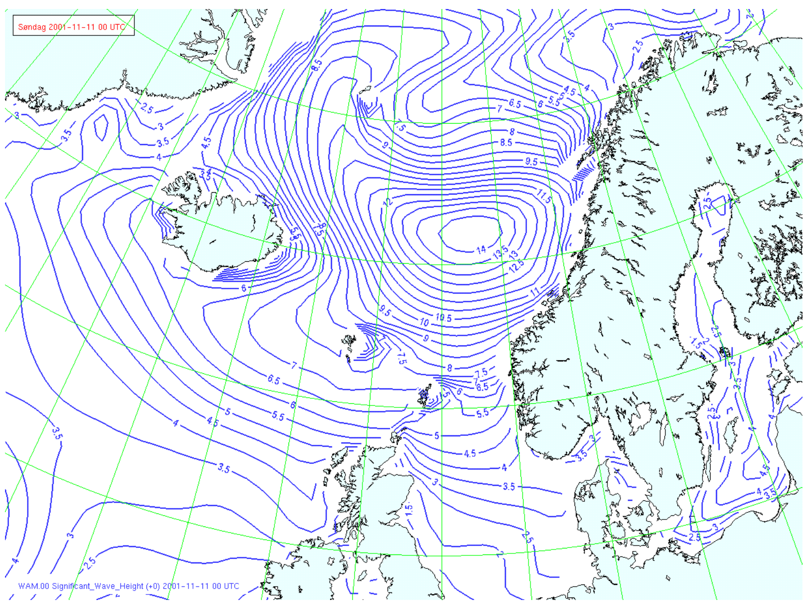

Figure 5: Contours of significant wave height from the operational wave model at the Norwegian Meteorological institute, 11th November 2001 at 00 UTC. Maximum Hs is well above 14m, close to WS Polarfront.

Directional wave spectra for this case are available from the operational wave model run at the Norwegian Meteorological Institute (WAM cycle IV). These are stored at 6 hourly intervals. The model is run with a spatial resolution of approximately 50 km. Directional resolution in the wave spectrum is 15 degrees, number of spectral bins is 25 (f_1=0.0420 Hz, f_{25}= 0.4137 Hz, f_i / f_{i-1} = 1.1). A new wind field from a 50km atmospheric model (HIRLAM) is input every 3 hours. Figure 6 shows a comparison of wind direction, wind speed and significant wave height at the WS Polarfront. These are from the hourly synoptical observations (put on the GTS). Wave measurements are calculated using two ship-mounted accelerometers and are based on 30 minutes sampling time. Wave spectra are stored onboard (every 90 minutes) and sent on monthly basis to the Norwegian Meteorological Institute. Significant wave height based on these spectra are also shown in Figure 6 (green line, 'Acc').

JONSWAP parameters were fitted to the observed spectrum and modelled spectra (WAM). Figure 7 shows the spectrum observed by Polarfront at 21 UTC, 3 hours before culmination. Gamma is very high for this high Hs value of 14m. It is lower at the peak of the storm (3.33). Figure 8 shows the JONSWAP spectrum fitted to the WAM output using the same scheme. One can see the fits are quite good. But the modelled spectra never reach the high peakedness values of observations. The values of σ_a and σ_b are quite different than recommended design values.

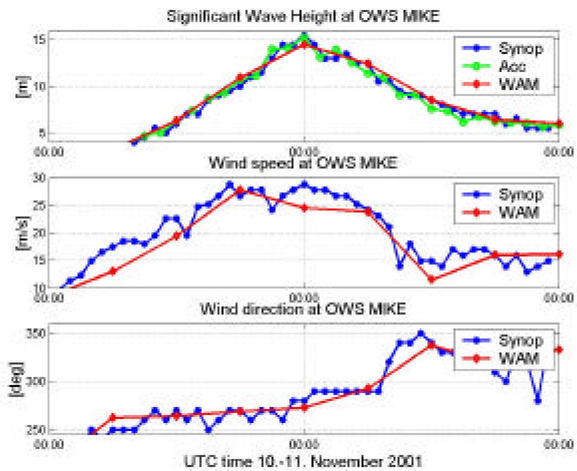

Figure 6: Hourly observations (blue line) from the WS Polarfront (OWS "Mike") of significant wave height (top panel), wind speed (centre panel) and wind direction (lower panel). Red lines are from 6 hourly wave model results (WAM), wind from the atmospheric model HIRLAM at wave grid point. Green line is Hs calculated from wave spectra based on 30 minutes sampling time from a ship based wave recorder, stored at 90 minutes interval.

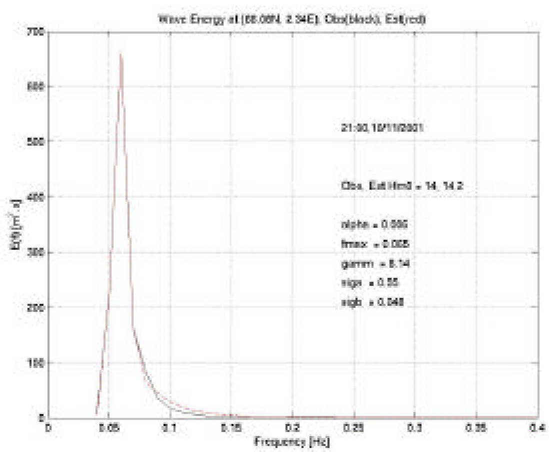

Figure 7: Observed and estimated JONSWAP spectra at the WS Polarfront at 21 UTC on the 10th November 2001. γ=8.14, σ_a=0.55, σ_b =0.048.

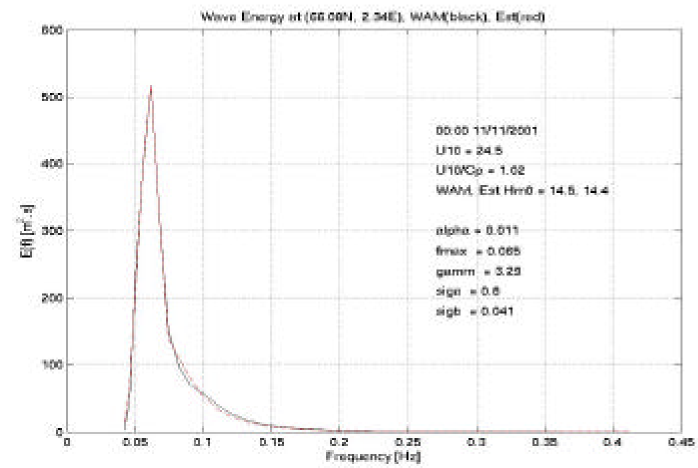

Figure 8: WAM and estimated JONSWAP spectra at the WS Polarfront at 00 UTC on the 11th November 2001. γ=3.29, σ_a=0.8, σ_b=0.041.

4. CONCLUDING REMARKS

We have shown here some examples of values that JONSWAP parameters can adopt, at the height of two storms producing high sea-states. One objective in the MAXWAVE project is to look for whether high values of JONSWAP gamma can be related to the likelihood of rogue wave development. For the two cases presented here, gamma has very high values for the observed spectra around the peak of the storm. In the case at Ekofisk the wave profile shows a high, steep crest but its height still falls within the expected range of standard statistical distribution models. It is likely that when such a wave field propagates (with continuous wind forcing) into shallower areas in the German bight, where the Stenfjell experienced wave damage, the waves can become steeper and break. Such waves may appear as high vertical walls, and could certainly be called rogue waves. The crew on the WS Polarfront also went through an ordeal in the high sea-state (15 m Hs) they experienced, as was reported in Television interviews afterwards. The WS Polarfront is built for staying on station, and being available for rescue work, in all weather conditions. There are no recorded wave profiles in the area, however the Heidrun platform did experience a ringing phenomenon (high frequency resonance in the structure). A special type of wave grouping is need for this to occur, along with a strong hit from a vertical wall of water (Sverre Haver, personal communication). This may be an indication of the presence of very high, breaking waves.

An obvious next step to make this work complete is to produce the WAM spectra over the time and location of the Stenfjell case. This work is ongoing and the results should be available shortly. We have seen that the JONSWAP parameterisation needs 5 parameters which all vary during a storm. Gamma only describes the enhancement of the peak. The narrowness of the peak is also relevant to the spectral shape thought to be necessary for rogue waves to develop via the Benjamin-Feir instability. Hence it will be necessary to include σ_a and σ_b in an evaluation of the fitted JONSWAP shapes or describe special features of the shape with some other parameter.

A challenge in the MAXWAVE project is to find examples of rogue wave events in the ocean for which we have good quality observations, and whose meteorological and oceanographical conditions can be simulated with adequate spatial and temporal resolution. Work is ongoing to analyse other cases for which the above is possible, such as the New Year's Day wave from Draupner.

5. ACKNOWLEDMENTS.

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