

EXTREME WAVE STATISTICS FROM TIME-SERIES DATA

Anne Karin Magnusson
Norwegian Meteorological Institute (DNMI)

Alastair Jenkins
Norwegian Meteorological Institute (DNMI)

Andreas Niedermayer (DLR)

José Carlos Nieto-Borge (DLR)

ABSTRACT

This work is a representation of wave time-series data used in the Maxwave project, with sample time series and statistics of wave height, crest height, trough depth. Data are included from the Ekofisk and Draupner oil fields, and from Belgian coastal waters. In addition, extreme value analysis, and also studies of corrected and evolved time series was performed.

INTRODUCTION

This report is prepared within the MAXWAVE Work Package 2 (WP2), which is to provide a data set on extreme wave statistics from in situ data (e.g. wave buoys, laser, and vertically-pointing microwave instruments), in order to analyse casualties, review design criteria used in the shipping and offshore industries, and to facilitate decisions regarding the safety of operations and personnel.

Time series from fixed moorings can underestimate the heights of extreme waves occurring in the vicinity, and the quasi-Lagrangian motions of wave buoys can underestimate the heights of the highest crests. In this work package, time series from various locations, in particular the Ekofisk field in the North Sea, are being analysed to derive analytical formulae for these underestimates.

The parameters to be extracted from the wave data include ratios of maximum to significant wave height and wave height to peak period, the distribution of extreme wave crest height and trough depth.

This paper is structured as follows: Section two deals with the description of the data series analysed within the WP2. Section three describes the sensors used in this work. Section four explains the analysis techniques used in WP2. Section five shows some of the

achieved results. Finally, the obtained conclusions appear in section six.

DATA SERIES ANALYSED

Ekofisk

This data set has been collected by Phillips Petroleum from the Ekofisk field in the North Sea. Observations have been stored in the environmental database at DNMI since 1980, and comprise wave profiles sampled at 2 Hz and other wave parameters calculated from 20-minute time series. They were stored at 3-hourly intervals until 1985, and in the period 1985-1995 the sampling was also made continuous in storm conditions (wind speed above 20 m/s or significant wave height above 4 m). Since 1995 the wave profiles from all 3 profiling instruments are stored continuously at the sampling rate of 2 Hz.

The instruments comprise one Datawell Waverider buoy and two vertically pointing lasers. The position of the Waverider buoy relative to the platform complex has varied, depending upon ship traffic in the area. The impact of the structure on the waves measured at the buoy has been neglected. Two downward-pointing Optech radars have been deployed on bridges near Flare North and Flare South in the platform complex since 1991. The measurements are considered to be point measurements (the diameter of the area at the water surface from which the signals are reflected is negligible). The Waverider buoy has an eigenfrequency of 30 seconds.

Draupner

Three time series of water surface displacement at the Draupner oil field, sampled at 2.1333 Hz using a downward-pointing laser instrument, were kindly provided by Statoil. 2048 samples were provided from a storm on 1995 January 1 at each of the following times: 15:20 UTC, 16:20 UTC, and 23:00 UTC.

reflection at the air-water interface. It is thus able to provide an absolute measure of the height of the sea surface at a fixed horizontal position, and in principle an accurate profile of the evolution of the wave form. It cannot, however, measure directly the surface slope, unless two or more sensors with a relatively close horizontal separation are used.

ANALYSIS TECHNIQUES

Spectral analysis and analysis of individual waves

The Ekofisk data were analysed using procedures described by Rijkswaterstaat in the Netherlands [8], with slight modifications. These comprised:

1. Rejection of poor-quality data points. This could not be done just by rejecting points which deviated by more than 4 times the standard deviation from the mean, since the purpose of MAXWAVE is to investigate extreme waves. The poor data were in general rejected by visual inspection.
2. Subtraction of the mean water level.
3. Spectral analysis involving performing fast Fourier transforms on 200-second subseries of the data, with cosine tapering on the outer 10 per cent of the subseries.
4. Splitting up the data into individual waves using the zero down-crossing criterion. Short waves with less than 1 second period were attached to the wave before: or the wave after.

The data are stored in tables in a SQL database using freely available database software (PostgreSQL): <http://www.postgresql.org/>. The parameters which are stored include the following:

- Time stamp in ISO format (YYYY-MM-DD HEMM:SS.SS+TTZZ).
- Recording interval.
- No. of samples (usually 2395).
- Table of individual wave heights.
- Table of individual wave periods.
- Total number of waves N .
- Height of the highest wave H_{max} .
- Average height of the highest 1/50 of the waves $H_{1/50}$.
- Average height of the highest 1/10 of the waves $H_{1/10}$.
- Significant wave height $H_{1/3}$ derived from the average of the highest 1/3 of the waves.
- Period of the longest wave T_{max} .
- Average of the period of the longest 1/3 of the periods $T_{1/3}$.
- Average of the period of the highest 1/3 of the periods $T_{H1/3}$.
- Maximum crest height H_{CM} .
- Level of lowest trough depth H_{TD} .
- Energy (variance) density spectrum at 0.01 Hz intervals $S(f)$.

- Significant wave height H_{m0} from spectrum (4 times the standard deviation).
- Spectrally averaged wave period T_{m02} .
- Frequency where $S(f)$ has its maximum f_p .

The cumulative distribution (CDF) of the individual wave heights, crest heights and trough depths for specific periods were also determined by sorting them into increasing order $\{1, 2, 3, \dots, N\}$. If i is the position in this ordering, the corresponding value of the estimated CDF is given by $F = i/(N + 1)$. The CDF values are fitted to Rayleigh distributions

$$F_R(x) = 1 - \exp[-(x^2 / 2 \beta^2)]$$

by estimating the parameter β from the variance of the data.

The data were also fitted to Weibull distributions

$$F_w(x) = 1 - \exp[-(x/\alpha)^\gamma]$$

Where α and γ are the parameters to be fitted by least-squares regression of $\log[-\log(1 - F)]$ against $\log x$, using the upper half of the data sample (i.e. $F > 0.5$). Alternative methods include the maximum likelihood method and the method of moments, but the least-squares fitting has the advantage of simplicity, and the upper half of the distribution was chosen as we are mainly looking for the upper extreme values. Fitting the whole sample by least squares regression is not so good, as the smallest values of wave height were found to cause a significant adverse (negative) bias in the parameter γ .

Correction of the Waverider measurements

The representation of the sea surface using floating instruments (buoys) differs from that of fixed instruments because buoys, having a quasi-Lagrangian behaviour, tend to stay in the troughs for a shorter period than in the crests. Longuet-Higgins [3] showed that this results in a reduced skewness (deeper troughs and lower crests), although overall parameters such as significant wave height and mean wave period are not changed significantly. Fixed (Eulerian) instruments such as vertically-pointing lasers give in principle a more accurate representation of the sea surface geometry. However, many more measurements are available from buoys than from Eulerian instruments, and so it is advantageous to employ a 'correction' technique to transform buoy measurements to hypothetical Eulerian measurements. (For Ekofisk, in the most severe storm ever recorded, on 1990 December 12, only buoy data are available because both laser instruments were out of order.)

Magnusson et al. [5] presented a correction method for the quasi-Lagrangian buoy behaviour. Correction of measurements from four storms increased the average water level by 10 cm, and some maximum crests increased by up to 50 per cent. The correction method is as follows:

1. The horizontal motion is assumed to be in one direction only.

2. The buoy is assumed to follow the fluid velocity at a depth of 0.2 m, corresponding to the centre of effort of the submerged section of typical accelerometer buoys. Stretching of the mooring is neglected.

3. Fourier analysis is combined with the superposition method of Donelan et al [2].

Figure 4 illustrates an example of quasi-Lagrangian correction method applied to a Waverider record registered in Ekofisk.

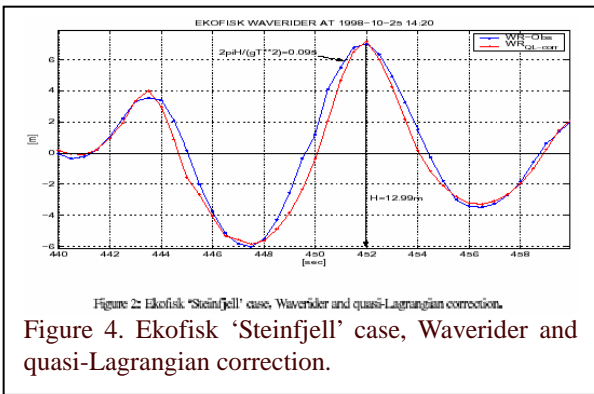


Figure 2: Ekofisk 'Steinfjell' case, Waverider and quasi-Lagrangian correction.

Figure 4. Ekofisk 'Steinfjell' case, Waverider and quasi-Lagrangian correction.

Propagation of wave elevation time series

The propagation of wave observations to other locations different from where the wave measurements are made, in order to evaluate the risk of extreme waves larger than those actually observed, is possible using Fourier analysis, with the different Fourier components being propagated with their characteristic group velocities. This is straightforward if the waves are assumed to be linear. Figure 5 shows the propagation of a Draupner time series using the linear method.

For weakly nonlinear waves, methods of propagation based on the (third order) nonlinear Schrödinger equation and higher-order theories, can be performed, which should also enable the simulation of the crest to trough asymmetry of steep waves. Figure 6 shows an example of asymmetric wave recorded by the Flare South laser at Ekofisk. In order to perform the nonlinear propagation, it is necessary to split the wave spectrum up into 'bound' and free waves. For data analysed in WP2, the following procedure was performed:

1. A characteristic frequency f_o is determined from the wave spectrum (a little greater than the peak frequency f_p derived from the power spectrum).

2. The free waves are assumed to have a frequency in the range $0 < f < 2f_o$.

3. Higher-frequency waves are assumed to be bound and not to propagate freely.

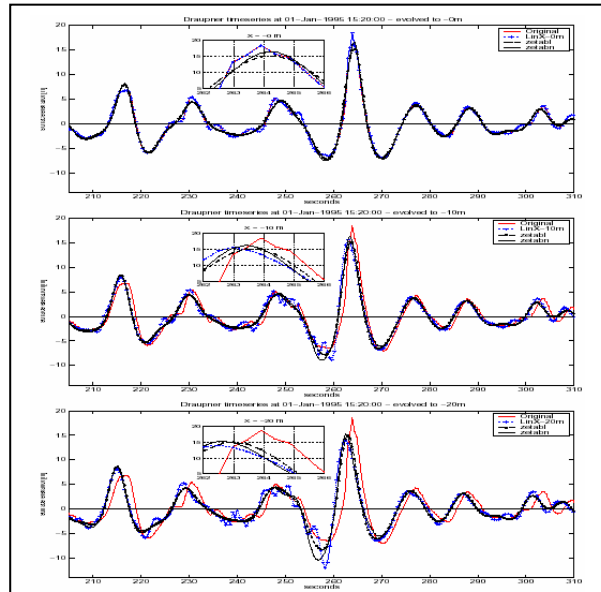


Figure 5. Linear propagation, Draupner storm of 1995 January 1.

Figure 8 shows an example comparing the

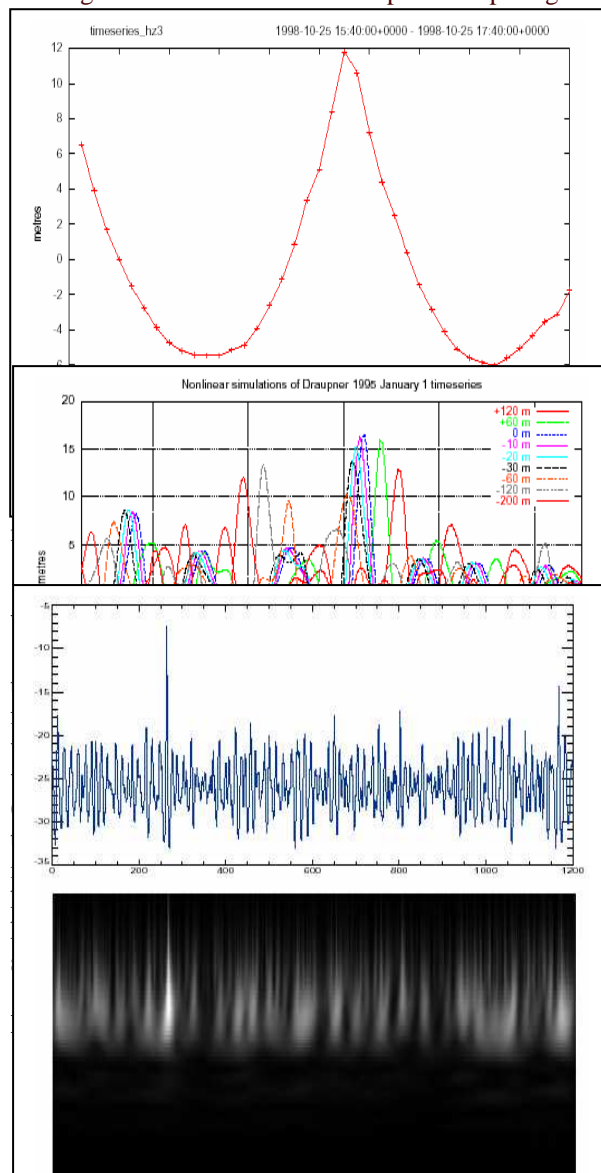


Figure 8. Detection of an extreme wave by wavelet

Relationship between maximum wave height, wavelength, wave period, and wave steepness

In Figure 9 an example is plotted showing some of parameters obtained from wave records of 2395 2 Hz samples. These parameters comprise significant wave height, maximum crest height, level of the deepest trough, and the mean height of the highest 1/50, 1/10, and 1/3 of the waves, for the Maxwave storm periods, and also corresponding maximum and significant periods. It can be seen that the parameter that most often becomes extreme in relation to the significant wave height is the maximum crest elevation. There is general agreement, particularly between the laser instruments in the periods where there is a tendency for these extremes, though not so much correspondence between individual records. For the laser instruments there is almost invariably a marked crest height : trough depth asymmetry for high waves.

The form of the extreme waves is physically reasonable: the example shown in Figure 6 shows a sharp crest, typical of either a breaking wave or an almost-breaking wave with a broad wedge-shaped 'Stokes corner flow' at the crest. For those cases, there is a greater asymmetry of the laser observation, and the fact that there the timing of the extreme events is not correlated between the different instruments (located up to 1 kilometre apart).

The distribution of extreme wave crest height and trough depth

Figure 10 shows an example of the cumulative distributions of wave height, crest height, and trough depth, for the Drauprier 1995 January 1 storm and the Ekofisk measurements during the 'Steinfjell' event. Both the Weibull and the Rayleigh distributions are in general reasonably good fits to the distributions, though we on occasion see noticeable discrepancies at the upper extremes. The asymmetry particularly in the laser observations between crest height and trough depth are noticeable for high waves. In some of the measurement series, a single extreme crest or a small group of crests can have a very noticeable effect on the very top of the distribution. It will be important in follow-up studies to evaluate the statistical significance of the fluctuations observed in the upper tail of the distribution. Such an investigation will require the data to be normalized with respect to dimensionless parameters such as the number of waves and the wave steepness.

CONCLUSIONS

The following conclusions can be drawn so far from the study:

1. The appearance of extreme waves, much larger than the surrounding waves, in a 'normal' time series, is

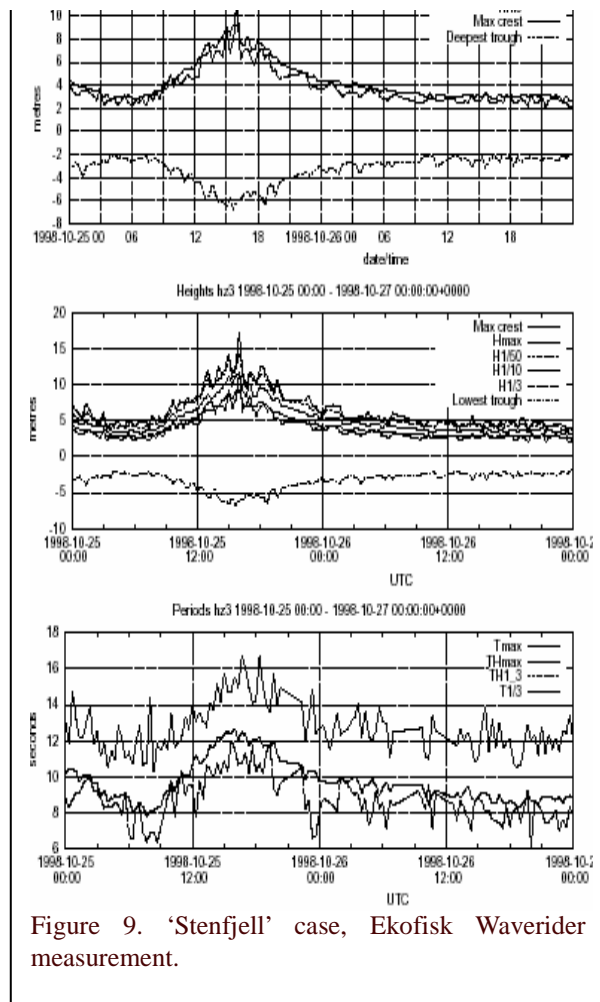


Figure 9. 'Stenfjell' case, Ekofisk Waverider measurement.

not unusual. Such waves do not have any unexpected physical properties: their shape is consistent with a normal breaking wave or a wave with a broad wedge-shaped 'Stokes corner flow'.

2. Extreme waves tend, particularly when measured with fixed instruments such as downward-pointing lasers, to have a marked crest-to-trough asymmetry, as would be expected for a wave with a breaking or near-breaking profile.

3. The statistics of individual wave height, crest height, and trough depth, are in general in agreement with Rayleigh or Weibull distributions. Extreme individual waves or small groups may, however, give rise to noticeable discrepancies for some measurement series. It is not yet determined whether these differences are statistically significant. The statistics also confirm the marked crest-to-trough asymmetry for large waves, when fixed instruments are used for the measurements.

4. Quasi-Lagrangian correction of a Waverider time series had only a small effect on the overall steepness of the wave, although the front steepness was increased somewhat.

5. The wavelet analysis method is very useful for detecting individual large waves.

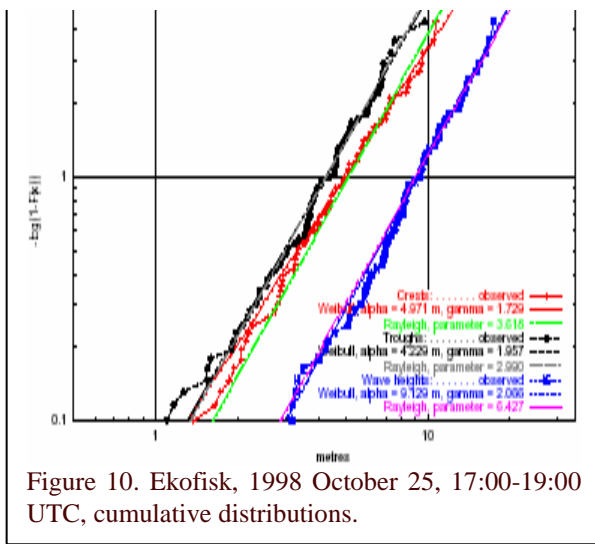


Figure 10. Ekofisk, 1998 October 25, 17:00-19:00 UTC, cumulative distributions.

6. Propagation of wave observations to hypothetical locations different from where the wave measurements are made, in order to evaluate the risk of extreme waves larger than those actually observed, may be possible, but if the extreme waves are significantly nonlinear, with crest height: trough depth ratios much greater than 1, then a linear propagation scheme will be insufficient, since it will in general predict maximum trough depths just as large as the crest heights. In the present study, both linear and nonlinear methods were used, but there is so far insufficient evidence to say how much better the nonlinear simulations are. For reasons of causality, propagation 'downwave', in the direction the waves are travelling toward, should be a much more stable and more reliable than propagation in the opposite, up-wave direction.

ACKNOWLEDGMENTS

This work was supported by the Commission of the European Communities under contract EVK:3-2000-00544 of the Fifth Framework Programme (Maxwave project).

The Ekofisk and Draupner data were kindly provided by Phillips Petroleum Norge and Statoil respectively. The Belgian coastal data were provided by the Coastal Service of the Ministry of Flemish Community.

REFERENCES

- [1] W. H. Buckley. A study of extreme waves and their effects on ship structure. Technical Report SSC320/SR-1281, DWTNSR&DC, Bethesda, Maryland 20084,1983.
- [2] M. A. Donelan, F. Anctil, and J. C. Doering. A simple method for calculating the velocity field beneath irregular waves. *Coastal Engineering*, 16:399-424, 1992. akm.
- [3] M. S. Longuet-Higgins. Eulerian and Lagrangian aspects of surface waves. *Journal of Fluid Mechanics*, 173:683-707, 1986. Reference to be supplied by Anne Karin Magnusson.

[4] A. K. Louis, P. MaaB, and A. Rieder. *Wavelets*. B. G. Teubner, Stuttgart, 1994.

[5] A. K. Magnusson, M. A. Donelan, and W. M. Drennan. On estimating extremes in an evolving wave field. *Coastal Engineering*, 36(2):147-163, 1999.

[6] S. G. Mallat. *A wavelet tour of signal processing*. Academic Press, San Diego, 1997.

[7] A. Niedermeier and W. H. Buckley. Analysis of 2d wave fields using a generalized hacym analysis. in preparation, 2002.

[8] Rijkswaterstaat. *The Rijkswaterstaat Standard for the Acquisition, Processing and Distribution of Hydrological and Meteorological Data from Operational Measurement Networks*. Directorate-General for Public Works and Water Management, Rijswijk, The Netherlands, 1995.