Abstract. An expert team at met.no in Bergen has been forecasting severe storms for Ekofisk since 1991, and for Valhall since 2004. Both oil fields are situated in central North Sea, about 30 km apart, and both are subject to subsidence, so that lower parts of the deck have increased probability of being subject to waves compared to initial design criteria. Risk reducing actions are therefore developed to ensure among other safe human activity on lower construction levels. Forecasting the extremes is today, for the Ekofisk eXtreme Wave Warning system (EXWW), focused on forecasting the significant wave height. Experience with 3 different in-situ measuring wave sensors at Ekofisk through monitoring of more than 100 storms has shown significant differences between sensors, showing a need for standardized methods in wave measurements, and that great care must be taken in extracting exact scientific relations for Rogue waves. It is also shown that forecasting significant wave height in extreme storms is still a challenge.

1. Introduction

“Rogue waves”, “freak waves” or “extreme waves” have in the past 10-15 years become common knowledge, in the sense that “everybody” knows they occur at times. The probable height of these and their cause is still a topic for research, with no proven relationships, therefore, activity at sea still relies on forecasting of significant wave height (Hs). An analogy is found in wind forecasting, where it is known that it is the gusts that provoke damages, but, extreme gusts, like extreme waves, are confined to small areas, and time and exact place for occurrence is not predictable with today’s knowledge. Methods for forecasting higher probability of occurrence are under consideration both for winds and for waves, but for the time being it is the average quantities like maximum 10 minute wind speed or 20 minutes significant wave height that are forecasted for the special users.

Forecasting the highest significant wave (Hs) in an energetic storm is also a challenge, as will be exemplified later. An expert team at the Norwegian Meteorological Institute (met.no) in Bergen has been monitoring and forecasting extreme waves for Ekofisk since 1991. Ekofisk is a platform complex, operated by ConocoPhillips, situated in the central North Sea (N56.5, E3.2, see Figure 1 and Figure 2). The extraction of oil in the ground under the platforms makes the soil deep below the sea bottom compress, making the platforms subside slowly. The subsidence varies geographically; at some platforms the subsidence has been of the order of 10m since start of production in 1971. Different actions to reduce the risk of wave impact on higher levels of the platforms have been taken: jack-up, that is elongation of the legs of some platforms by 6m (1987); installation in 1989 of a 100m high concrete wall, approximately 30 meters above mean sea level, to surround and protect the
central processing platform (2/4-T, the ‘Tank’); Water injection; building of new
platforms in an east going axis from the old complex (Ekofisk II, started in 1998);
decommissioning of platforms north of the tank, and the tank.

On 12th December 1990, the most severe storm ever recorded at Ekofisk made
numerous damages on platforms in the North Sea. Hs was measured at the maximum
to 13.2m with a Waverider buoy, a value at the order of a 30-50 year return period. It
induced the start of EXWW, Ekofisk eXtreme Wave Warning, where an expert team
updates special forecasts every 3 hours in severe storms.

In the first years of EXWW, the necessary risk reducing actions offshore could be
taken at 3 hours pre-warning. Since 2-3 years, new procedures include demobilisation
of some platforms, which in the most severe cases will need complete demobilisation,
requiring about 1000 people to be flown onshore. This is due to take many hours.
Therefore actions around this demobilisation must be started already 2-3 days before
culmination in a storm. This decision is of course an important one to take, with high
economic consequences. There are a number of uncertainties to be considered when
deciding when to do what in the extreme storms. A combination of statistics and
experience is used by the companies to decide what level of Hs to use for different
actions. Forecasting skill on Hs is one of the important values to know. Different
studies have been carried out to quantify the forecast skill of the forecasters and the
models. Some results are presented hereunder.

Validation of forecasts needs high quality of measurements. Ekofisk has now four
different wave sensors (Figure 2) that send data in real time to a server at met.no,
making Ekofisk one of the best wave instrumented offshore site in the world. The real
time monitoring and the validation work performed have shown high short time
variability in the measurements, and considerable differences in between the
measuring systems, and this is presented in the following section.

Rogue waves are for waves like the ultimate ‘gusts’ in the wind. Knowledge on the
heights and forces involved is still un-complete, as there are only few quality
controlled measurements of the most exceptional ones, the most famous being the
Draupner wave on 1st January 1995. Statistics between rogue wave events and
parameters that are suggested to be related to events have failed to prove any
relations,(Olagnon and Magnusson, 2004, and Krogstad et al, these proceedings). But
this is not surprising, since we know that a singular extreme wave in a sea state may
happen in an area but not at a measuring site. This is known because of damages at
high levels of constructions, while records are not made of similar heights at
measuring sites. Statistics from a limited number of high storms will therefore
probably not give certain relationships.

Forecasting the extreme significant wave height in intense and severe storms is a
challenge of its own. An example of prognoses during the storm on 9th November
2007 is given hereunder to demonstrate this.
2. The wave sensors

Phillips Petroleum Norway, now ConocoPhillips, have recorded waves at or in the vicinity of the Ekofisk complex since 1980. Different sensors have been used, and mounting locations on the complex have changed through time. In the years 1991 to 1993, environmental data were available through modem. Since 1993 data have been transferred in real time through internet. The first winter season (1991-1992) learnt us that the wave data from two height measuring systems (an EMI radar and a Plessey radar) were largely affected by lee effects from the tank (Figure 2). High focus was thereafter put on good quality wave measurements, because forecast skills are highly dependent on measuring feedback. A WAMOS (www.oceanwaves.de) was installed to measure directional wave spectra at 2/4-K, and two new sites were chosen for 2 down looking lasers (Optech lasers), one at flare South, with good exposure to waves from east-west direction, and one at Flare North, with relatively good exposure to northerly directions, and also from the east and west sectors. This paper only deals with the wave measurements from the in-situ systems (wave profilers). The two Optech lasers have given relatively good measurements in the period 1995-2005, although with known problems of possible reflection of waves from the tank in northerly situations at the northern flare, and sea spray from the platform legs in the vicinity of both sensors when waves are large, not always as much as seen in the picture in Figure 3 showing the southern part of the Ekofisk complex during a storm.

Due to decommissioning of the platforms North of the tank, the sensor at flare North was replaced in 2005 with a new system of 4 lasers in an array on the bridge between 2/4-K and 2/4-B (Krogstad et al, these proceedings). The bridge is oriented East-West, with open sector towards North and South. Waves from westerly sector may be subject to interference with the 2/4-B platform, which is about 80 meters away. The sensor at flare South was replaced with a MIROS down-looking radar altimeter, a Miros Range Finder (MRF).

A non-directional waverider buoy has been measuring free-field waves since 1980. Data return from this system is quite high. Batteries are changed outside the winter season, a procedure started after a stormy winter not allowing for replacement for a long time.

3. Quality of measurements

Experience from monitoring the wave data from different sensors during storms in real time has given useful knowledge on quality of wave measurements. Discussions with system providers have also revealed that sampling and filter techniques are used to filter inevitable bad samples occurring from time to time. This results in apparently good and smooth wave profiles, from which detail wave information can be extracted. Details about this filtering is outside the scope of this paper, but some points seem necessary to report here in view of the validation results given, and in perspective of the conferences goal, getting more knowledge about rogue waves.
The measurements of significant wave height from the waverider buoy (WR) have always been looked at as reference data, although it is a wave-follower. Waves are measured as un-skewed (Magnusson et al., 1999), but wave height from crest to trough will still be correct, and so is the significant wave height considered to be. It has been reported earlier that buoys may disappear under the water surface at approach of high crests (probably steep and very high crests). In 2006 new software was installed at Ekofisk to treat the Waverider data in real time. For a period there were very noisy data, out of range or unvalid. It appeared that when the buoy was submersed, the datastream from the buoy to the receiving station at the platform was broken. The missing data were filled with default numbers (large negative), being part of the analysis, and making large erroneous data. The solution adopted then by the system provider was to filter the data in real time to keep the reporting as continuous as possible. Despite this discrepancy the Waverider buoy is still regarded as a reference at Ekofisk.

The MIROS altimeter (MRF) is seen to give lower maximum Hs in storms compared to the WR (Figure 3), also in directions where there are no sheltering effects expected. WR data have also been compared to measurements from a SAAB altimeter at Valhall, (Figure 4), operated by BP. The same discrepancy is observed to WR data. Correlation is good but slope of regression lines shows that Hs at the Waverider is about 10% higher than at the down looking sensors at Ekofisk and at Valhall 30 km away. Through a meeting with MIROS we learnt that a spike removal filter was running on the raw data from the MRF to ensure stable data return in real time. In Figure 5 we see a picture of an extreme wave passing the construction supporting the bridge north of the sensor at Flare South, causing a lot of sea spray (and green water in this case). Hs is not known at time of picture, but probably somewhere between 10 and 12m. Sea spray is believed to occur (and to cause erroneous data) even when waves are lower. The spike removal is necessary, but it also filters too large acceleration in data, smoothing high crests. This alters the statistics of the wave crests, and may be part of the cause giving lower Hs values when waves are steep. The discrepancy is seen through all ranges of Hs. Not surprisingly, because steep waves occur in all ranges of Hs. A more thorough investigation is necessary to quantify the discrepancies in wave profiles and Hs values.

The LASAR, a system of 4 lasers in an array mounted on the bridge between 2/4-B and K, were configured by Mark Donelan and no filtering is used on the raw data, which are sampled at 5Hz. The measuring procedure gives unfortunately a lot of spikes. The lasers used in this configuration are from the same manufacturer (Optech) as the sensors used at Flare South and North in the period 1995 to 2005, but the new sensors in the LASAR system have lower intensity due to more restrictive rules (related to eye-safety). So far the analysis of storm data has shown that significant wave height can be higher with the LASAR system than with the WR but the difference is not quantified yet.
4. Variability in Hs

All 3 sensors at Ekofisk measuring the wave profile at 2 and 5 Hz show similar behaviour in short time variability of Hs, see example from the Andrea storm 8th to 9th November 2007 in Figure 6. Hs values can differ by 2 meters (20%) from one 20 minute record to the next from the same sensor. Just after midnight measurements vary between roughly 6.5 and almost 10m, regardless of sensor. To demonstrate the variability we have evaluated the one-, two- and three-hourly running means of Hs from the WR in the same period of time shown in Figure 6, and the standard deviation between the Hs values within these intervals. The evolution of these averages are shown in Figures 7, 8 and 9, with envelopes at the standard deviations. Maximum Hs in storms decreases from 11m (the maximum 20 minutes value) to Hs (1-hrly)=10 m, Hs (2-hrly)= 9.6 m, and Hs (3-hrly) = 9.54m. The mean and maximum standard deviation of data included in the data within the period of time shown in the figures changes from respectively 0.57 m and 1.75m in the one-hourly data to 0.78m and 1.23m in the 3-hourly data.

5. Validation of ECMWF forecasts in 9m-storms or larger

Because of new safety procedures at Ekofisk and Valhall, an exact forecast of highest significant wave height in a storm is necessary 3 days ahead of the culmination time of the storm. A threshold of 9 m in the forecasted Hs at culmination, 3 days in advance, is used for triggering special preparedness offshore and onshore within the companies (ConocoPhillips and BP). In very extreme storm events, up to around 1000 persons must be flown to shore from the Ekofisk Complex, and around 200 persons from Valhall to shore. New platforms are being built that will soon make demobilisation unnecessary. Until then, there is high interest in the forecast skills.

The most important question for deciding which thresholds to use for the different actions to be taken are: how accurate is the forecaster’s prediction at three and two days in advance? How accurate are the long range forecasting models in extreme storms? To answer these questions, forecasts given in storms that gave around 9m or more at Ekofisk in the period 2000-2007 were analysed. There are not that many cases with Hs above 9m at Ekofisk. We can count 38 such storms since 1980, six winter seasons had none, while two had four. Tools and models for forecasting are under continuous improvement, so that doing statistics on model prognoses many years back in time is not relevant for forecast uncertainty today. The number of real time data has also increased in this period through increasing number of satellites and regular flights measuring wind, temperature and humidity in the atmosphere and wind and waves on the sea surface.

Validation has been performed on forecasts issued every 3 hours during EXWW storms, but before the unmanning of the platforms was relevant, EXWW forecasts were not issued more than 15-24 hours ahead of culmination. Results of the validation of these warnings issued in storms with wave height higher than 9 meter in the period
1991 till today, 30 in number, show a forecasting skill (here being the average error between max forecasted and max observed 20 minutes Hs) varying between -.2 and -.5m in average up to 24 hours ahead of the maximum in storm. The wave model prognoses run at met.no have larger errors, varying from a deficit of 1 meter in average up to 24 hours before, and of 2 meters up to 60 hours ahead of culmination. The wave and atmospheric models at met.no are run over a limited area up to 60 hours, with higher resolution than the global models run at ECMWF. Error statistics for the ECMWF forecasts of significant wave height at Ekofisk are shown in Figure 10. Maximum values of forecast are extracted regardless of timing, some storms had stored output every 3 hours, but standard was 6 hours. The storms considered are from January 2002 to March 2007. All errors are shown with different symbols for different runtimes up to 96 hrs ahead of maximum in Figure 11.

Several updates of the model system at ECMWF have been made. For instance going from about 55 km resolution to 25 km resolution in January 2006. Figure 11 shows that the storm after this improvement in resolution gave high score in November 2006, but other storms thereafter showed again a deficit of 2 meters and more. The fact is that one never really will be sure of if an extreme situation is well forecasted in advance. Consistency in forecasts from the different meteorological institutes permits to evaluate the probability of a development by looking at the similarities and consistencies. There are also different probabilistic forecasts produced that may help in the decision making, but some more analysis has to be done on the value of these to make use of them in offshore operations and this service in special.

In the next section the different forecasts in the Andrea storm are presented.

6. The Andrea-storm

The form and development of a depression, including the propagation direction across the sea area of interest is very important for what the culmination height will be. Spectral shape parameters that may be used for extreme wave warning will also be dependent on this development.

The Andrea storm, which name was given for the EXWW services only, must be said to be well forecasted. The severity was quite well predicted, in that Hs at the 9 to 10 meter level were modelled 2-3 days ahead, though with variations from one run to the next available 6 or 12 hours later. EPS (Ensemble Prediction System) runs from ECMWF gave early storm wave height culmination at 9 to 10 meter level at Ekofisk with high probability already 4 days in advance. An example is given in Figure 12, showing wind speed, Hs and Tp EPS-forecasts starting at the 6th November 2007 at 12 UTC. These prognoses are available around 10-12 hours after analysis time, in this case 54 hours before culmination in storm.

Figure 13, 14 and 15 demonstrates how varying the storm development was predicted from one run to another. In Figure 13 two different predictions of Hs from ECMWF
are compared (+84 and +96 hours). Although Hs is 9 meters at Ekofisk in both cases, the area of 9m in the +96 hours forecast (blue lines and colouring) is relatively correct compared to analysed fields, but in the forecast 12 hours later (+84 hours, red lines and colouring) the strongest field is forecasted to be more to the west, reflecting another storm development. Figure 14 shows 3 different model prognoses for situation on 8th November 2007 at 18 UTC (ECMWF; met.no’s WAM50km, which is WAM run with 50km resolution with winds from a 20 km resolution atmospheric model (HIRLAM20); WAM10km which has 10 km resolution and is forced with winds from HIRLAM with 12km resolution). All these predictions were available around two and a half days before maximum in storm, and they all predict the storm maximum to be located W - NW of Ekofisk (5, 8 and 9.5m) while the maximum occurred closer to the Norwegian coast.

Closer to storm culmination (+33 hours) all 3 models agree more on where the maximum will occur. ECMWF gives 9 meters in an area NE of Ekofisk. The coarse met.no WAM model (50km) gives 10 m in almost same area, and the fine grid model WAM10km peaks above 11m just North of Ekofisk at that time. Figures 7-9 show that there is a higher degree of severity between 03 and 09 UTC on November 9th. The closer to culmination time, the closer to the Norwegian Coast the maximum wave field is. WAM10km evaluates maximum Hs to be 11.5-12 m in the Norwegian trench NE of Ekofisk on the 9th at 06 UTC, with between 10 and 10.5m at Ekofisk. Which is quite close to the observed maxima, but slightly above the maximum one-hourly averaged Hs from WR.

7. Conclusive remarks

The Andrea storm was what we can call a well forecasted storm. Long in advance (3-5 days) predictions from ECMWF, both deterministic and from the Ensemble Prediction System (EPS), gave values of maximum Hs in the storm close to what was observed. It underpredicted the 20 minutes maximum value, but was close to the 3 hourly average value. Finer resolution models run at met.no gave Hs predictions slightly higher, comparing better with running average values of Hs over shorter period (one hourly).

The Andrea storm was a challenge to predict even if forecasts were good in average. Risk reducing actions had to be taken 2-3 days in advance, and the value of expected maximum 20 minutes value of Hs is used as criteria.

Small differences in atmospheric developments of a severe storm may give large differences in significant wave height at one location (50-100%). Large differences (not quantified herein) in the spectral shapes may be expected, and probably also in the wave profile statistics (crest, trough, steepness). Analysis of an extreme wave event is dependent on a good storm track history.

Wave measurements are seen to be sensor dependent. The analysis of wave data from the different sensors at Ekofisk and Valhall Ekofisk demonstrates the need of an improved description of spike removals from the system providers, and of standardisations in wave data sampling.
8. Acknowledgements

Thanks to Jean Bidlot at ECMWF for providing the ECMWF forecasts for Ekofisk in the period 2002-2007.

9. References


Figure 1 Ekofisk in central North Sea (N56.5, E3.2), southernmost point in Figure), operated by ConocoPhillips, and Valhall (N56.3, E3.4, close to Ekofisk), operated by BP. Isolines for bottom topography. Grid lines every 5 degrees.
Figure 2 The platform complex Ekofisk (N 56°30', E 3°12'), and instrumentation for environmental data, viewed from south. The two platforms in the east branch are built in 1999 and 2002. The central platform 2/4-T, also called the Tank, is the platform inside the concrete wall that was put in place in 1989. The wall has a diameter of 120 meters, is 100 meters high of which about 30 meters are above mean sea level. In the north we see the two platforms 2/4-K and 2/4-B, with the bridge in between where the new LASAR system is mounted.
Figure 3: Comparison between significant wave height $H_s$ ($H_s > 1m$) from the Waverider and the MIROS Range Finder (MRF) at Ekofisk, for the period 2007.

Equations:

$Y = 0.88 \cdot X + 0.12$

$N_d = 36203$

$Cor = 0.97$
Figure 4 Comparison between Hs (>1m) from the Waverider at Ekofisk and the Saab radar at Valhall in 2007.

Figure 5 Flare South is the tower to the left in the picture. An extreme wave breaks through the support of the bridge just north of the site where one down-looking wave
sensor (Optech laser at the time of the picture) is mounted.

Figure 6 Example of a storm record (9th November 2007, the Andrea storm at Ekofisk) showing how significant wave height from the 3 sensors at Ekofisk vary with time. $H_s$ can vary with almost 2m (20%) from one measurement to the next.
Figure 7 One hourly running averages of the Waverider during the Andrea storm at Ekofisk, 9th November 2007. Blue dots: 20 minutes records, Red line: one hourly running average on the 20 minutes significant wave heights from the Waverider. Blue stippled lines: the one hourly averages +/- the standard deviation between the 3 records in each hourly average.
Figure 8 Two hourly running averages of the Waverider during the Andrea storm at Ekofisk, 9th November 2007. Blue dots: 20 minutes records, Magenta line: 3-hourly running average on the 20 minutes significant wave heights from the Waverider. Black stippled lines: the 3-hourly averages +/- the standard deviation between the 3 records in each 3-hourly average.
Figure 9 Three hourly running averages of the Waverider during the Andrea storm at Ekofisk, 9th November 2007. Blue dots: 20 minutes records, Cyan line: 3-hourly running average on the 20 minutes significant wave heights from the Waverider. Black stippled lines: the 3-hourly averages +/- the standard deviation between the 3 records in each 3-hourly average value.
Figure 10 Validation of the wave model prognoses from ECMWF in storms with culmination height 9 meter or more, up to 4 days ahead. Storms from the period 2002 to March 2007. Only maximum Hs is used, time of maximum may vary up to 12 hours to observed value. Red bars: mean error in forecasted maximum in storm. Yellow bars: standard deviation of the difference.
Figure 11 Validation of the wave model prognoses from ECMWF in storms with culmination height 9 meter or more, in the period 2002 to March 2007. Only maximum Hs is used (from the quality controlled data and using 20minutes values), time of maximum may vary up to 12 hours to observed value. Different symbols for different start times of the model, up to 4 days ahead.
Figure 12  ECMWF EPS prognoses of wind speed, Hs and peak period (Tp) at Ekofisk, giving high probability for Hs around 9m on 9th of November. These results were available just before midnight on the 7th, around 54 hours before culmination.
Figure 13 Significant wave height at 9th November 2007 at 00 UTC in the +84 hours (red lines, isolines every meter) and +96 hrs (blue lines) from ECMWF. The oldest is the closest to analysed fields (maximum 20 minutes and one-hourly values from the Waverider at Ekofisk are 11m and 10m respectively).
Figure 14 Significant wave height at 8th November 2007 at 18 UTC in the +54 hours from WAM10km (blue lines, isolines every half meter, max Hs = 9.5m), and +66 hrs from ECMWF (green lines, max Hs = 8m), and +60 hours from met.no’s WAM 50km (max hs = 5m). Here the storm maxima are all in western part of the North Sea.
Figure 15 Significant wave height (isolines every half meters) on 8th November 2007 at 21 UTC in the +33 hours forecasts from the ECMWF model (green lines, max Hs is 9m), the Norwegian coarse WAM model (dark blue, max Hs is 10m), and the Norwegian fine grid (WAM 10km) model (light blue, max Hs is 11m). Ekofisk location is indicated with a red cross.

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Mean and std of 1-2-3 hourly averages of Hs_waverider
Maximum Hs (Waverider) = 10.95m

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