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“THREE SISTERS” MEASURED AS A TRIPLE ROGUE WAVE GROUP

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ABSTRACT

On November 30, 2018, our attention was caught when analyzing wave profile time series measured by a platform mounted wave sensor (a SAAB REX radar) at Ekofisk, central North Sea. The 20-minute time series had not only one, but three consecutive waves with individual heights that all were more than twice the significant wave height, the two last of them being almost equally high with a factor 2.35 to the significant wave height of 4m (from $4\sigma(\eta)$, over 20 minutes).

Counting three rogue waves in one sequence seems to be very rare. In this study we analyze how the shape is evolving in space and time using linear and non-linear propagation methods developed by Mark Donelan [1,2] and Karsten Trulsen [3,4]. Weather conditions and characteristics of the sea state with the ‘Three Sisters’ (named the “Justine Three Sisters”) are presented. It is found that the Three Sisters occurred in a crossing sea condition, with wind sea and swell coming from directions 60 degrees apart, with about same frequency, but very different energy.

Keywords: Rogue waves, “Three Sisters”, wave statistics, linear and non-linear propagation of waves.

INTRODUCTION

The “Three Sisters” term has been known for decades due to several reports of ships encountering not only one monstrous wave, but three large consecutive waves. Several reports can be found on ships experiencing near disaster conditions in the

encounter of “Three Sisters”. For example, the American ice-breaker *Polar Sea* off Vancouver Island in October 1985, when two distinct groups of three extreme waves coming from a direction distinct of the prevailing wave direction, made the ship roll 50° from one side to another. One man was killed. The accident happened during the night and the height of the waves was not possible to see [5]. Another one is a report from February 1963, when the French naval-training cruiser *Jeanne d’Arc*, sailing with a broken starboard shaft towards Hong Kong for repairs, spotted some huge breakers in the horizon, behind a flatter patch of waves. A description on how the captain prepared the already damaged ship to meet the waves can be found in [5]. The result was that the three waves lifted the ship three times, made her plunge into the troughs thereafter, tilting 30-35° each time. The escorting ship did not experience the same waves, but saw *Jeanne d’Arc* disappear three times under the horizon. The wave group was described as short-crested, the length of the crests being about 100 m wide, with relatively short wave lengths (~100m). Similarities between the two cases seem to be that the wave groups came from directions about 20° off the prevailing wave conditions. One of them to starboard, the other to port side.

The cruiser *Norwegian Dawn* on April 16, 2005 was damaged off the coast of Georgia after the encounter of what is described as a series of three large waves [6]. As happened also with the cruiser *Louis Majesty* on March 3, 2010 in the Mediterranean sea close to Barcelona [7].

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The phenomenon of three large waves coming in a group has been called ‘Three Sisters’ in literature and media, and also the ‘Glorious three’. It has been encountered several times in history, but instrumental observations are less known. Usually, statistics of rogue waves reported in the literature are made searching for the absolute maximum in a time series. But neighboring wave crests and troughs are important as well for the stability of ships.

In the present paper, we describe “Three Sisters” recorded by a SAAB REX radar at Ekofisk (a ConocoPhillips operated platform complex at 56.5°N, 3.2°E, in central North Sea) on November 30, 2018. Weather conditions at the time of the event and other wave recordings are analyzed to find out more about sea state conditions. In particular, a question to answer is whether the event occurred in a crossing sea state or not. Further, we investigate how this wave group is evolving using linear and non-linear wave models and provide spectral and statistical properties of the sea state in which it occurred.

THE MEASURED THREE SISTERS

Figure 1 shows an extract of continuous wave profile measurements (here duration 50 minutes) recorded by a SAAB radar at Ekofisk on November 30, 2018. Vertical lines indicate the start of each 20-minute timeseries. The middle timeseries includes three consecutive waves being of exceptional height compared to the surrounding waves in the wave record. Such groups have been mentioned in the literature as “Three Sisters”. We will denote this record with the acronym “3RW” herein. We propose also to name the case as the “Justine Three Sisters”, as this is the Polish name-day given to this date (November 30).

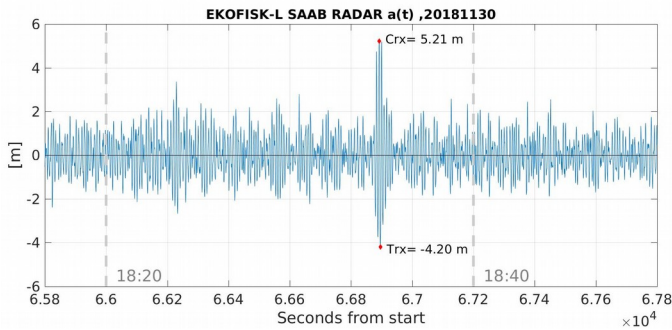


FIGURE 1: WAVE PROFILE AS MEASURED DURING 50 MINUTES INCLUDING THE TRIPLE ROGUE WAVE (3RW). VERTICAL LINES INDICATE THE START AND END OF THE 20 MINUTES TIMESERIES IN WHICH THE 3RW IS MEASURED. UTC TIME MARKED INDENT AT BOTTOM IN GRAPH IN GREY. X-LABELS ARE SECONDS FROM START OF DAY (00:00UTC).

These three consecutive waves have individual heights that are all equal to or more than twice the significant wave height (see Figure 2). The three consecutive highest trough-to-crest values (or “*zd*”: zero-downcrossing values) are: 7.8, 9.0, 9.4m, with factors to H_s (≈ 4 m) of 1.95, 2.25, 2.35. The three consecutive highest crest-to-trough values (or “*zu*”: zero-upcrossing values) are: 8.7, 9.4, 8.5m, with factors to H_s being 2.18, 2.35, 2.13, while the three crests are 4.9, 5.2 and 5.2m, with factors 1.23 and 1.3 to H_s .

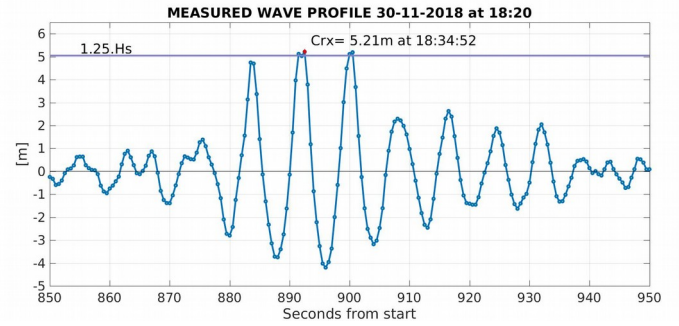


FIGURE 2: THE GROUP WITH THREE ROGUE WAVES AS MEASURED WITH A SAAB RADAR. SAMPLING FREQUENCY IS 2HZ. MAXIMUM CREST IN THE 20 MINUTE TIME SERIES (AS WELL AS OF ALL DAY) IS MARKED WITH A RED DIAMOND.

The last two crests of the “Three Sisters” have identical maximum crest heights (5.2m). The highest trough-to-crest height is the third (9.4m), but highest crest-to-trough value is the second (also 9.4m). Both ways (*zd* or *zu*), when rounding a bit, we get highest factor of H_{max} to H_s to be 2.35.

Except for the first crest factor being 1.23, which is very close to 1.25, we can state that all three waves are satisfying both rogue wave criteria given by Haver [8],

$$\frac{H_{max}}{H_s} \geq 2.0; \frac{C_{max}}{H_s} \geq 1.25 \quad (1)$$

where H_{max} denotes the zero-crossing maximum wave height, C_{max} is the maximum crest height. Krogstad et al. [9] were the first to denominate waves satisfying both conditions as “double rogue waves”. We have here three consecutive double rogue waves, what we call a “Triple Rogue Wave group”, “3RW” for short.

One may note that the hourly H_s is 3.7m when evaluated using wave profile data from 18 to 19 UTC (including the 3RW). The factors of highest individual height (9.4m) and crest (5.2m) to H_s increase from 2.35 to 2.54 and from 1.30 to 1.41 respectively when comparing to the hourly value of H_s instead of the 20-minute value. This underlines even more how large this wave group is compared to the sea state in general at that time.

The significant wave height through the day was quite stable, between 3 and 4 m. The 20-minute values of significant wave height (H_s) have, as can be expected due to the short sampling period, a high variability (Figure 3, blue thin line with dots), and is the largest at the time of the 3RW. The 60-minute (red line) and 180-minute values (3 hours, cyan line) are also shown. Values are updated every 20 minutes. The 3-hourly values indicate there is a slight increase in wave energy, starting from about 16 UTC to 21 UTC that day, and that the 3RW case occurs during the increase phase. The question arising from this observation, is if the increase is due to local wind increase, or to the entering of another wave system at the location. Weather conditions are presented in the next section with some local metocean values at the location.

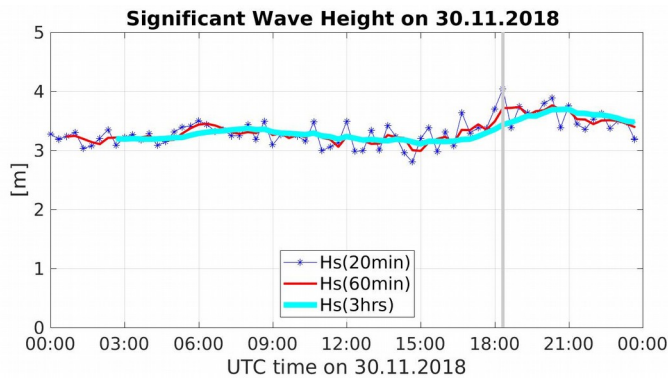


FIGURE 3: SIGNIFICANT WAVE HEIGHT HS THROUGH NOVEMBER 30 2018 AT EKOFSK USING 20, 60 AND 180 MINUTES OF WAVE PROFILE MEASUREMENTS, UPDATED CONTINUOUSLY EVERY 20 MINUTES. VERTICAL GREY LINE INDICATES TIME WHEN 3RW IS MEASURED.

WEATHER CONDITIONS

Weather maps (not shown here) from November 28 to December 1, 2018, show that the period starts with a high pressure over southern Norway and the North Sea. No swell systems of importance to the measurements analyzed here are expected to be produced at far distances. A complex low system develops in the North Atlantic November 27, moving eastwards towards the Norwegian Sea. This produces a southerly wind field in the North Sea, starting in the evening of 27th. The wind at the location of the measurements is the most intense on the 28th, with maximum wind speeds nearing 20 m/s (37 knots), building up a significant wave height of 6 m. Wind and wave observations as reported by the environmental system at Ekofisk and sent in real time to MET are shown in Figure 4.

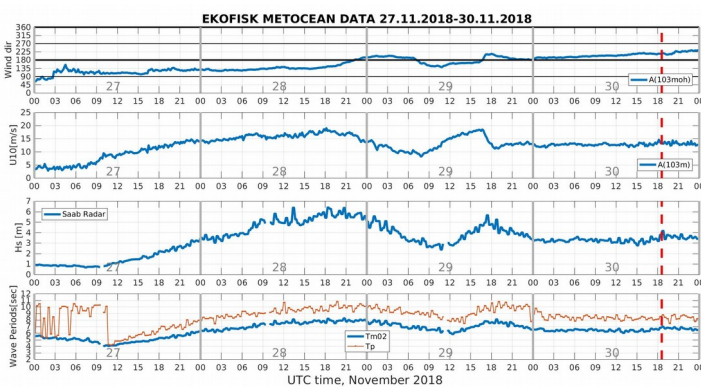


FIGURE 4: WIND AND WAVE OBSERVATIONS AT EKOFSK (56.5°N, 3.2°E) FROM NOVEMBER 27 TO 30, 2018. FROM TOP TO BOTTOM: WIND DIRECTION, WIND SPEED, SIGNIFICANT WAVE HEIGHT AND WAVE PERIODS (BLUE: MEAN WAVE PERIOD TM02, RED: PEAK WAVE PERIOD TP). VERTICAL GREY LINES ARE AT 00UTC EVERY DAY. THE VERTICAL RED DASHED LINE ON LAST DAY INDICATES THE TIME OF OCCURRENCE OF THE 3RW.

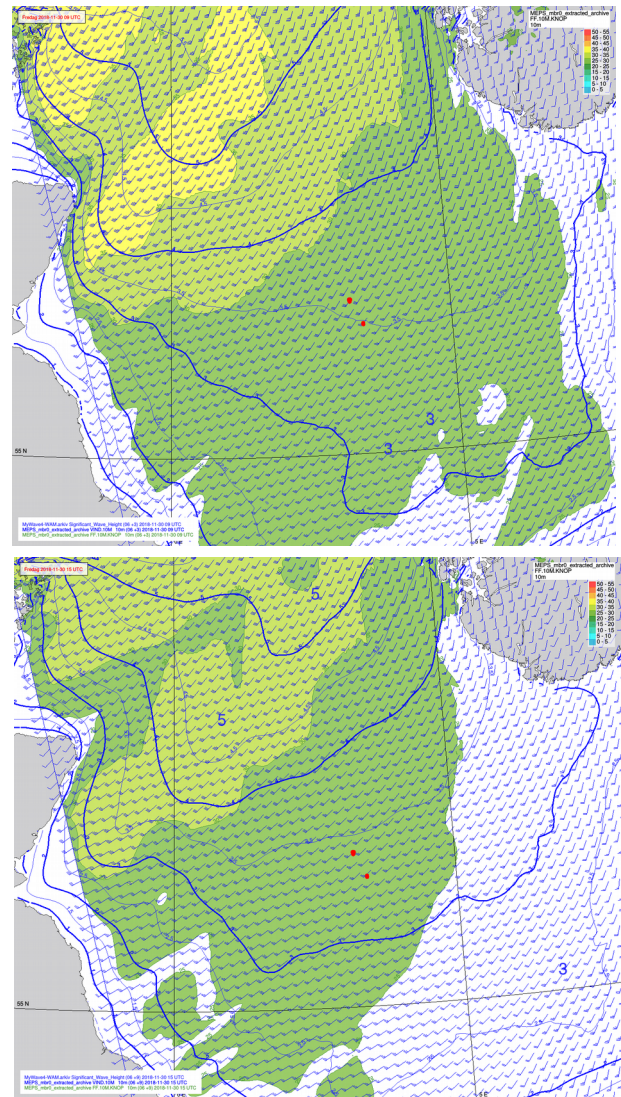


FIGURE 5: WIND (AROME 2.5KM) AND WAVES (WAM4) IN THE NORTH SEA ON 30.11.2018 AT 09UTC(TOP) AND 15UTC. WIND ARROWS AND COLOURED AREAS FOR WIND SPEED (FF) IN KNOTS: GREEN: 25<FF<30, LIGHTGREEN: 30<FF<35, YELLOW: 35<FF<40. ISOLINES OF SIGNIFICANT WAVE HEIGHT: THIN LINES EVERY 0.5M, THICK LINES EVERY 1METER. TWO RED DOTS INDICATE POSITIONS OF EKOFSK(56.5°N, 3.2°E) AND VALHALL (56.4°N, 3.4°E).

A second wind increase towards 20 m/s is also seen on the 29th, with a more moderate increase in Hs (5-5.5m). Wind direction has now veered from southeast to southerly. From late on the 29th (18UTC) to the end of the 30th wind speed is rather constant at Ekofisk (~13-14 m/s), slowly veering from south to southwest (230° at end of day), with significant wave height stabilizing at around 3.5m. On the 30th from about 15 to 18UTC, we see a slight increase in wind speed and Hs (about 1-2 m/s and 0.5m). The 3RW group occurs at a wind direction of 216°, wind speed around 13m/s, in a veering condition: the wind field veers gradually to westerly in central North Sea and areas west of Ekofisk in the afternoon on the 30th.

Weather maps showing wind speed and significant wave height in the North Sea at 09 and 15UTC (2-3 hours prior to the 3RW) are shown in Figure 5. These are from MET-Norway's operational wave model named "MyWaveWAM4" (implemented at MET Norway under the project MYWAVE), using WAM Cycle 4.5.4 version HZG. The wave model is run with 4km resolution (denoted WAM4) with 36 direction and frequency bands, and forced by MET's regional atmospheric model AROME run at 2.5 km resolution [10]. Both models, AROME and WAM4, use boundary conditions obtained from ECMWF-IFS (Integrated Forecasting System).

The 2D and 1D wave model energy distributions at 06, 12 and 18 UTC are shown in Figure 6. The wave model is run with a 10 degree directional resolution. The wave spectra show that the wind sea is gradually veering from SSW (205°) towards SW. But at 18 UTC the 2D-spectrum is bimodal due to a wave system coming from about 280°. The weather maps show no wind direction being westerly in the area west of Ekofisk in the hours prior to 18 UTC. What we can see is that the wind is slightly stronger in the region east of the Scottish Highlands (Figure 5), and northwest of Ekofisk, producing a small increase in wave height up towards 4m in the afternoon in that area. Although produced by southwesterly winds, and propagating mainly northeast, we believe that the small increase in H_s at Ekofisk is an effect of incoming energy from the area with higher wave generation. Wave energy spreads to both sides of main wind direction, thereby producing the bimodality visible in the wave spectra in Figure 6.

A question is if this bimodality is real. Directional wave information is available from two other wave systems at Ekofisk as well. The sensors are mounted on 2/4-K, a platform about 1.5 km further north of the measuring site of the 3RW. We here show measurements only from the WAMOS, a sensor based on a X-band marine radar technology.

Directional spectra from WAM4 (left) and WAMOS (right) are shown in Figure 7, with directions at the horizontal axis and frequencies at the vertical axis (top panel). The directional distribution of the frequency integrated spectra are in the bottom graphs. Mean and peak directions are indicated with vertical lines, as well as wind direction from model (short line). We see the directional distribution is unimodal at 00 UTC, and bimodal at 18 UTC. Mean direction deviates more from the peak direction in the observed directional distribution compared to the modeled one.

The peak direction in the model is slightly more westerly than the observed one (225° vs 206° as calculated from the frequency integrated spectrum, P_{dir1dr} in legend). The peak frequency of the incoming wave system from west is equal to the one of the wind system at the beginning of the hour (18UTC, not shown here) but is gradually moving to lower frequencies at end of that hour, becoming as indicated by the model spectra at 18UTC.

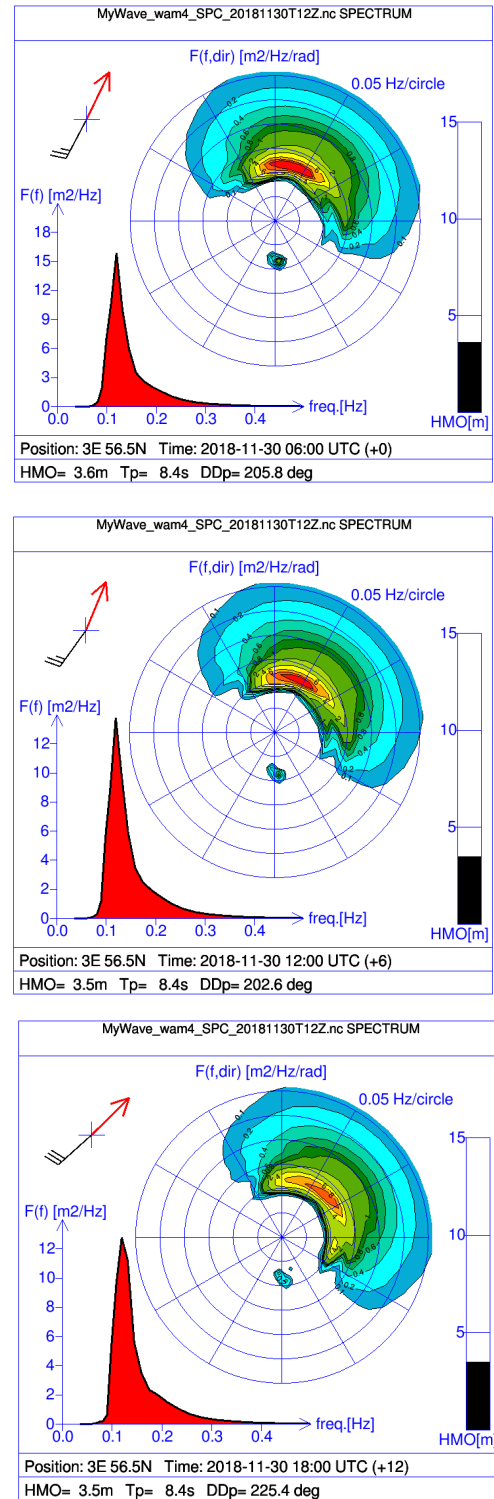


FIGURE 6: 1D AND 2D WAVE SPECTRA FROM WAM4 RUN WITH START TIME 30.11.2018 AT 12UTC (FROM LEFT TO RIGHT: VALID TIMES: 06, 12 AND 18 UTC). ARROWS IN TOP LEFT SHOW WIND ARROW IN BLACK (1 SHORT LINE: 5KNOTS, 1 LONG: 10 KNOTS) AND PEAK WAVE DIRECTION (RED, 'GOING TO') WHICH IS ALSO GIVEN IN TEXT ('COMING FROM') AT BOTTOM.

STATISTICS OF THE SEA STATE WITH “THREE SISTERS”

As mentioned in section 3 the sea state including the “Three Sisters” is bimodal. The 20-minute sea surface elevation time series containing the 3RW has a skewness of 0.36 and a kurtosis of 5.2, indicating a strong deviation from a Gaussian process (skewness 0 and kurtosis 3). Otherwise, kurtosis is quite stable through the day, on average 3.06. Skewness is on average 0.15 over the day, being at that level in the 2 hours previous to 18 UTC. Directional spread (see Figure 7) is 35.8 in the model and 33.8 as measured by the WAMOS. Both sources indicate a directional spread around 30° from 04 to 15 UTC, then, in the increasing period of H_s , spread increases gradually to 35° and stays at that level from 19 UTC to end of day.

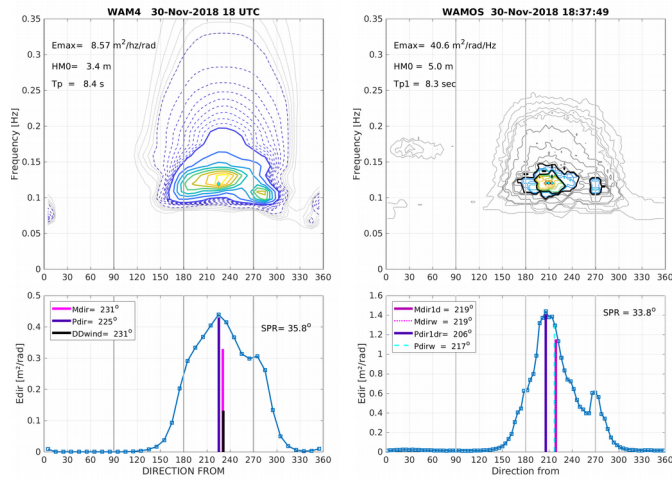


FIGURE 7: DIRECTIONAL SPECTRA AS MODELLED BY WAM4 (LEFT), AND MEASURED BY WAMOS (RIGHT). VALID TIMES: 18UTC. TOP: $E(f, \theta)$ AND BOTTOM: DIRECTIONAL DISTRIBUTION OF FREQUENCY INTEGRATED WAVE ENERGY ($E(\theta)$).

Figure 8 shows hourly directional distribution from the model from 12 to 20 UTC. Thick black line is distribution at 18UTC. This indicates that the 3RW case occurs in the growing phase of the westerly swell system, and before (or at the onset of) the windsea starting increasing in the new direction 220°.

The observations confirm the existence of bimodality at the time of occurrence of 3RW with an angle difference of 60 degrees which is evaluated as difference between 270° (direction of secondary wave system) and ~210° (peak wave direction) as measured by the WAMOS. The two wave systems have approximately the same peak frequency but the wind sea system contains much more energy than the swell one. These conditions are different from the ones during the Louis Majesty accident [7] when both wind sea and swell had about the same energy and peak period, however, approximately the same crossing angle as in the 3RW case.

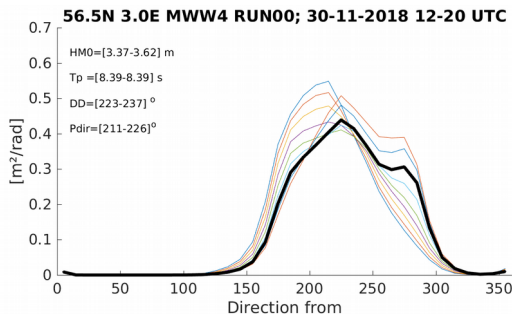


FIGURE 8: DIRECTIONAL DISTRIBUTION USING WAM4, EVERY HOUR FROM 12 TO 20 UTC. PEAK DIRECTION IS 211° AT 12 UTC, AND 225° AT 18UTC. THICK BLACK LINE IS FOR TIME 18UTC, THE CLOSEST TO THE 3RW OCCURRENCE.

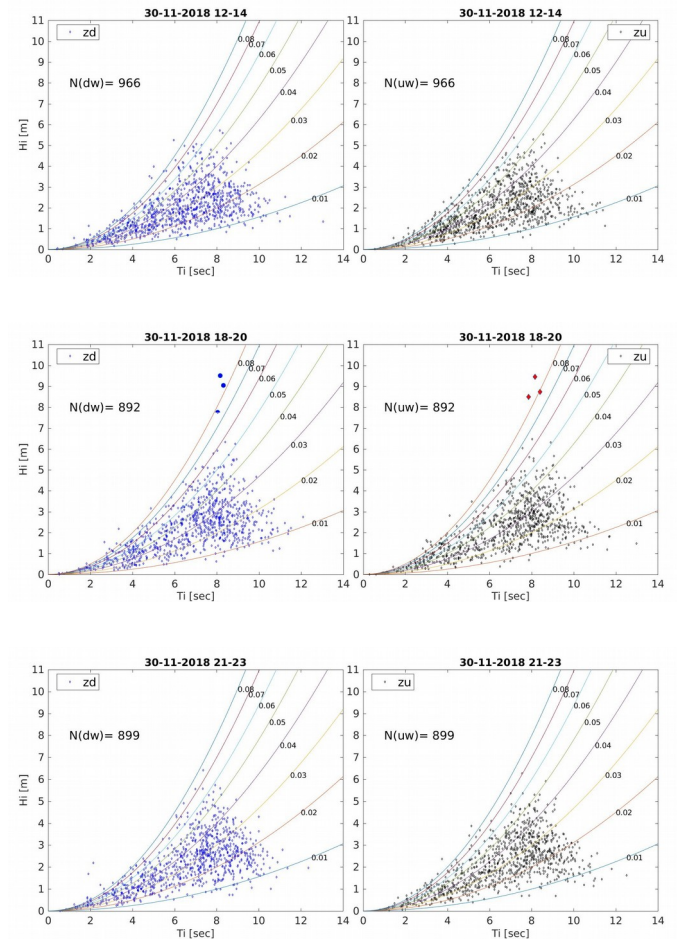


FIGURE 9. DISTRIBUTION OF INDIVIDUAL WAVE HEIGHT ON INDIVIDUAL WAVE PERIODS RESULTING FROM DETERMINISTIC ANALYSIS OF WAVE PROFILE MEASUREMENTS ON NOVEMBER 30, 2018. LEFT: ZERO DOWNCROSSING VALUES, RIGHT: ZERO UPCROSSING VALUES. FROM TOP TO BOTTOM: INDIVIDUAL WAVE HEIGHTS FROM PERIODS 12-14 , 18-20, AND 21-23 UTC. FILLED CIRCLES AND DIAMONDS (IN FIGURES FOR 18-20 UTC) ARE VALUES FROM THE 3RW GROUP. LINES FOR WAVE STEEPNESS FROM 0.01 TO 0.08 ($= H_i / 1.56 \cdot T_i^2$). NUMBER OF WAVES $N(dw)$ AND $N(uz)$ IN EACH TIME PERIOD OF DAY IS INDENT.

A deterministic analysis of the wave time series is performed to select individual wave heights (H_i) and periods (T_i) to investigate evolution of their joint probability of occurrence (scatter diagrams). Values from zero-up and -downcrossing analysis are shown separately in Figure 9. Data are also retrieved from different phases: before (12-14 UTC), during (18-20 UTC) and after the event (21-23 UTC). The different groups seem to have different types of wave regimes. As the evolution of directional spectra indicate:

- at first (1), around 12, we have a unidirectional spectrum in a decaying phase (as indicated in Figure 8).
- intermediate phase (2): 18-20: the swell is coming in.
- after veering (3): 21-23, a broad spectrum.

In phase 2 we have more steep higher waves than in phase 1. Phase 2 has the "Three Sisters" peaking out of the mass. The phase is in a crossing wave system according to the directional information available, with incoming weak swell at the same frequency as main wave system. In phase 3, number of very steep waves is decreasing. There are a few more high steep waves in the zd than in the zu classes, indicating forward front steepness is somewhat higher. Waves cluster towards longer periods.

EVOLUTION OF WAVE TRAIN WITH "THREE SISTERS".

A question arising is if the 3RW group transforms through propagation from or to a group with even higher maximum height in the group. And how high this could become. Any wave group will disperse, with longer wave components overrunning the shorter ones as they propagate faster. In order to investigate how the shape of the wave group is evolving in space and time, linear and non-linear propagation methods are used here. One linear method (called here MDL) is developed by Mark Donelan [1,2]. Two methods based on the Schrödinger equation for water waves are developed by Karsten Trulsen, including a linear method called LS and a nonlinear method according to the modified nonlinear Schrödinger (MNLS) equation also known as the Dysthe equation [3,4].

Using the measured 20-minute timeseries starting at 18:20, propagation was done upstream and downstream assuming long-crested waves. This is a very rough assumption, and it is to be expected such computations will have short validity in space and time. The wave length of these waves is around 100m (wave period of the three largest is about 8s). Analyzing evolved waves beyond a few wave lengths would probably be beyond acceptance.

The two linear methods appear to give quite similar results. Figure 10 shows the development of the wave train using LS method upstream and downstream 1000m, with intervals of 100m. Figure 11 shows evolved time series using the MNLS method. The computations were done assuming long-crested waves by means of the spatial propagation version of the modified nonlinear Schrödinger (MNLS) equation described in [12].

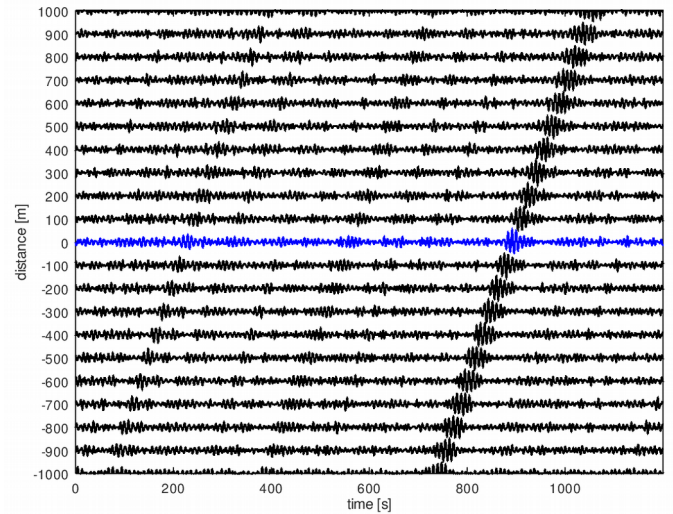


FIGURE 10: SIMULATED WAVE PROFILES AT DISTANCES FROM -1000M TO +1000M (INTERVAL: 100M) FROM LOCATION OF MEASUREMENTS. IN BLUE: WAVE PROFILE AT LOCATION. METHOD: LINEAR SCHRÖDINGER (LS).

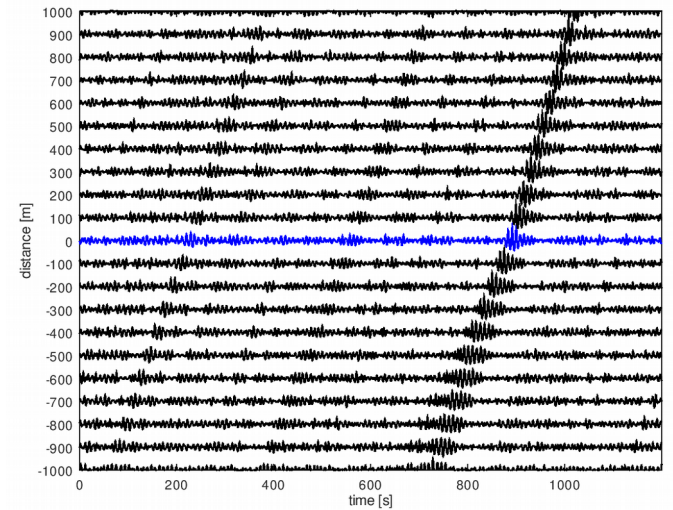


FIGURE 11: SIMULATED WAVE PROFILES AT DISTANCES FROM -1000M TO +1000M (INTERVAL: 100M) FROM LOCATION OF MEASUREMENTS. IN BLUE: WAVE PROFILE AT LOCATION. METHOD: MNLS (MODIFIED NLS).

The simulated time series are shown at consecutive intervals of 100 m, up to 1 km distance up and downstream. According to the validation tests in [12] the deterministic propagation should not be taken beyond this distance since we do not have directional measurements for initialization of short-crested waves.

A wave group will change its shape partly due to linear dispersion and partly due to nonlinear modulation. In this case it seems that nonlinear modulation changes the shape of the group much faster than what linear dispersion alone would have done. The wave group propagates faster than in the linear simulations. Figure 12 shows H_{max} values from the evolved

time series. We see MDL and LS solutions are similar (MDL solutions are given every 20m). MNLS has a different solution, with H_{max} increasing from upstream to downstream. Development of the highest crest (not shown here) has a steeper increment than H_{max} , while deepest trough keeps constant.

Both linear solutions give a maximum crest and height that is higher than measured at distances about ± 200 m from location. Factors of maximum Crest to H_s increase slightly to both sides of the propagation in the linear simulations (from 1.29 to 1.35-1.38). Factors of H_{max} to H_s increase from 2.32 to about 2.5. The spacial development using MNLS simulations differs, in that upstream, the factors are lower than at the origin, and slightly higher downstream. The shape of the wave groups at 200m up and downstream of location, and at location, using the three methods, are shown in Figure 13. Note that values at measuring location ($d=0$) in the MNLS data are already quite higher than observed. This is due to MNLS being run in long-crested mode, thus reconstructing the nonlinear wave field with bound waves according to an incorrect directional distribution.

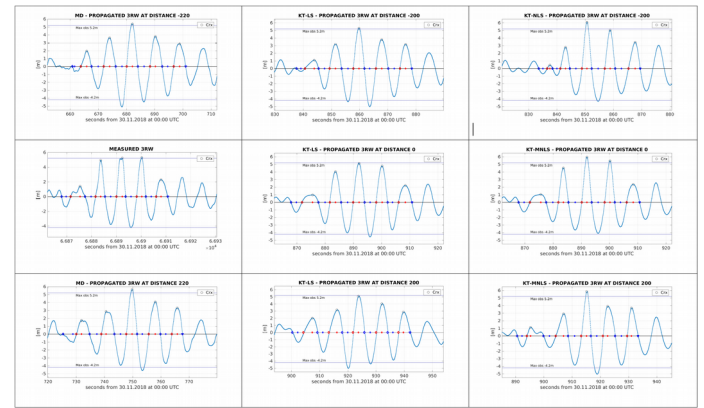


FIGURE 13: WAVE PROFILE AT -200, 0 AND +200 M (TOP TO BOTTOM) FROM LOCATION OF MEASUREMENT USING THREE METHODS FOR PROPAGATION (FROM LEFT TO RIGHT: MDL, LS AND MNLS). HORIZONTAL LINES MARK MAXIMUM OBSERVED CREST AND TROUGH HEIGHTS (5.2 AND -4.2M).

CONCLUSIONS

The study describes the sea state with three consecutive Double Rogue Waves, called the “Justine Three Sisters”, recorded by a SAAB radar at Ekofisk on November 30, 2018. The associated weather conditions are analyzed and the statistics of the sea state provided. They appeared in a crossing sea condition with angle between wind sea and swell being 60 degrees, but with swell energy much lower than the wind energy. Not many measurements of “Three Sisters” are reported in the literature, so the study contributes to further insight to the rogue wave phenomena.

Both linear and nonlinear spatial evolution of the wave train with the “Three Sisters”, the non linear evolution being carried out by the modified nonlinear Schrödinger (MNLS) equation, in the upstream and downstream direction show that the wave group with the “Justine Three Sisters” was quite long-lived. It may have had even more than three siblings prior to reaching target location, and slightly higher individual waves (height and crest maxima) are probable at a position not too far from location of measurement.

The wave conditions described are expected to impact operational conditions of ships and marine operations in general [13].

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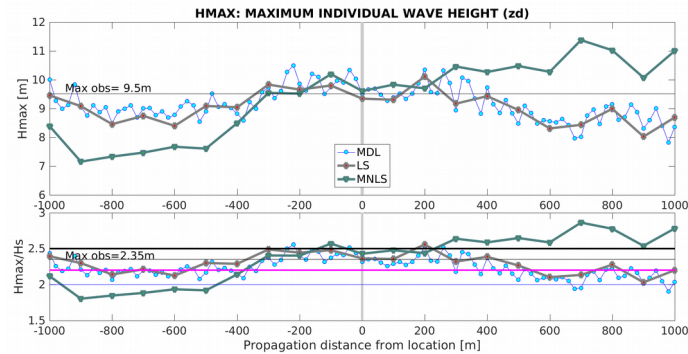


FIGURE 12: TOP: MAXIMUM HEIGHT (H_{MAX}) RETRIEVED FROM MEASURED (AT DISTANCE = 0 M, CENTRE, INDICATED BY GREY VERTICAL LINE), AND FROM PROPAGATED TIME SERIES UP AND DOWNSTREAM 1000M. BOTTOM: FACTORS H_{MAX}/H_s AS FUNCTION OF DISTANCE TO LOCATION. THREE PROPAGATION METHODS: MDL, LS, MNLS ARE SHOWN.

The MNLS results may indicate that the “Three Sisters” are measured at an intermediate stage of the nonlinear dispersive focusing of the group. We suspect that the focusing further develops into a narrower group with higher waves downstream from the measurement location. As the modulated group becomes narrower and higher, its propagation speed increases. The highest individual waves eventually accumulate at the front of the group.

The analysis indicates that the wave group with the “Three Sisters” was quite long-lived, and may have had even more than three siblings prior to reaching target location.

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