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EXTREME WAVES AND WAVE EVENTS IN THE BALTIC SEA

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ABSTRACT

Records of free-surface elevations from the Polish territorial waters are analyzed with emphases on the presence of extreme waves, wave groups and extreme wave events occurring in the Baltic Sea. The results are applied to derive extreme wave statistics and to eventually indicate periods and areas where extreme waves occur more frequently.

INTRODUCTION

Studies of sea waves in the Baltic Sea have a long history in Poland, although systematic observations of wave heights started over 20 years ago. The results of numerous projects have found applications in many fields, such as shore protection, design of maritime construction, etc. However, still increasing number of accidents related with extreme waves require much better understanding of the extreme sea conditions. Knowledge of extreme waves, wave groups and extreme wave events is particularly significant. Some progress in that field can be achieved by the analysis of data sets containing reliable measurements.

A unique set of time series of free-surface elevation records is available in the Institute of Hydroengineering of Polish Academy of Sciences, Gdańsk. It consists of measurements obtained by Waverider and Directional Waverider buoys, located at several points placed along the Polish coastline of the Baltic Sea. It comprises of almost 25000 records including storm conditions.

INPUT DATA

The measurements of free-surface elevation were conducted in the southern part of the Baltic Sea at three buoy stations located in the Puck Bay, in the vicinity of Niechorze (Pomeranian Bay) and Lubiatowo. The locations of all measuring points are shown in Figure 1.

Figure 1. Chart of the coast of Baltic Sea and locations of buoy stations.

Table 1. Localization of buoy stations and periods of measurements.

Type of gauge	Name of place	Latitude N Longitude E	Water depth (m)	Distance off-shore (km)	Period of measurements
WR	Lubiatowo	54º 49’ 17º 50’	7	1	28 Sep 89 - 19 Oct 89
WR	Lubiatowo	54º 51’ 17º 50’	20	7	9 Nov 90 - 8 Dec 90
WR	Puck Bay	54º 26’ 18º 45’	15	6	27 Sep 91 - 7 Oct 91 22 Oct 91 - 01 Nov 91
WR	Puck Bay	54º 26’ 18º 43.’	15	6	20 Aug 92 - 12 Dec 92
DWR	Puck Bay	54º 27’ 18º 43’	16	7	22 Aug 95 - 21 Dec 95
DWR	Puck Bay	54º 26’ 18º 43’	15	6	22 Aug 95 - 4 Jan 96
DWR	Lubiatowo	54º 51’ 17º 48’ (54º 51’ 17º 48’)	20	5	01 Nov 96 - 31 Jan 97
DWR	Niechorze	54º 09’ 15º 03’	18	6	18 Apr 97 - 9 May 97 05 Sep 97 - 14 Jan 98
DWR	Lubiatowo	54º 53 17 º 51	20	5	15 Jan 98 – 31Aug 99
DWR	Lubiatowo	54º 50’ 17 º 48’	20	5	10 Oct 00- 21 Oct 01
DWR	Lubiatowo	54º 51’ 17 º 50’	20	5	05 Sep 02 – 04 Dec 02

The measurements were performed using both Waverider (WR) and Directional (DWR) Waverider buoys. Their periods varied from a few to several months. Some basic features of buoy stations, their locations and measurements periods are given in Table 1 (Paplińska, 1995).

Puck Bay

The Puck Bay is a part of the Bay of Gdańsk, which is separated from the Baltic Sea by the Hel Peninsula. Taking into account this specific geographical location, it can be assumed, that a wave field in the Puck Bay consists of waves coming from two different sources namely, waves generated on the short fetches in the Bay of Gdańsk and the waves generated on the long fetches in the Baltic Sea (Paplińska, 1995).

The measurements, using both the WR and the DWR, were performed successively in four points close to each other. The total number of records for the Puck Bay is 2757.

Niechorze

Niechorze is a village located in the eastern part of the Pomeranian Bay. Waves are generated there on the fetch limited by Bornholm Island and the West Baltic coastline.

All measurements were performed using the DWR. The entire set of 2801 data records was collected.

Lubiatowo

Lubiatowo village is located in the middle part of the Polish coastline. The coastline is there straight on a long section. A sea bottom is characterized by the presence of well-formed set of four longshore sand bars.

Measurements at Lubiatowo started earliest, in 1989 and were performed first using the WR and next DWR. The total data set coming from this period comprises of 19664 records.

DATA ANALYSIS

From the described foregoing measurement data sets, there were selected individual waves coming up the assumed criterion, on the basis of which the extreme waves can be determined. Such waves in a case of the Baltic Sea were defined as:

- waves exceeding twice the significant wave height $H_{max}/H_s>2$,
- significant wave height is larger than $H_s>1$m.

The application of this definition resulted in 414 extreme wave records, which is sufficient to perform a short-term statistical analysis. Most of records (330) come from Lubiatowo, 63 from Niechorze, and 21 from the Puck Bay.

It is worth noticing, that some definitions impose other restrictions on extreme wave height, regarding the fore going and the following wave heights and/or the ratio of the crest to trough wave height (Chien *et al*, 2002). However, they are rather more suitable in the analysis of episodic waves. Extreme waves considered in the present study can be rather regarded as the wave events or large waves characterized by the extreme values of the tail of statistical probability distribution.

Additionally, a continuous storm that occurred in Pucka Bay in 1995, characterized by H_s >1, lasting over 3 days was measured. It should be emphasized that it is a unique data set worth more detailed analysis.

Some records of *in situ* measurements intrinsically involve biased data and "spikes". Thus, in order to remove data errors, it was necessary to perform a visual quality control of records. Because of a time-consuming nature of such control, only some specified "extreme" wave records have been completely checked.

The wave rose for the area of the Puck Bay obtained on the basis of DWR measurements, is shown in Fig. 2. The plot in Fig. 2 also shows the exceedence probability of wave height in different direction. It is seen in Fig. 2 that the waves with H_s greater then 1m are coming mainly from NNE-N directions.

The maximum measured height of an individual wave was 6.1 m and the highest significant wave height was 3.5m. The significant wave height exceeding 1.0 m occurred 15% of time and over 2 m 1%, respectively.

In the Puck Bay a number of 21 extreme wave records has been found in the total number of 2757 records. It is worth noticing that the largest waves come from the N direction.

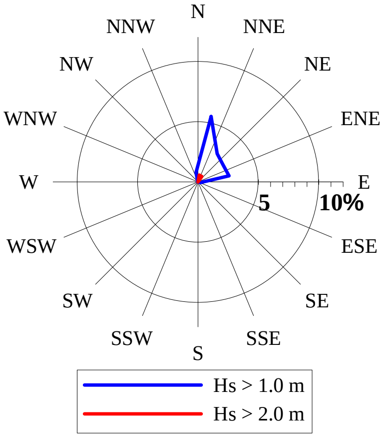

Figure 2. Wave rose of significant wave height for measurements taken in the Puck Bay.

The wave rose for the area of Niechorze is presented in Fig. 3. The plot in Fig. 3 shows that waves with H_s greater then 1m come mainly from W-NW and N-NE direction.

The maximum measured height of an individual wave was 6.5 m and the highest significant wave height was 3.3 m. The significant wave height exceeding 1.0 m occurred 37% of time and greater than 2 m - 5%, respectively. The number of 63 extreme wave records was found in the total number of 2081 records. It is interesting to notice that the largest waves come from the NW direction.

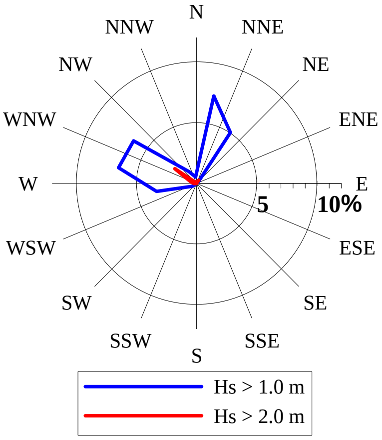

Figure 3. Wave rose of significant wave height for measurements at Niechorze.

The wave rose for the area of Lubiatowo is presented in Fig. 4. It is seen that waves with H_s greater then 1m are coming mainly from W-WNW and N-NNE directions. The biggest measured height of an individual wave was 7.6 m, the highest significant wave height was 4.0 m. The significant wave height exceeding 1.0 m occurred 29% and greater than 2.0 m - 6%, respectively. The total set of 330 extreme waves has been observed among 19664 records. It has been found that the majority of the largest observed waves came from the northern direction although some of them came also from the western direction.

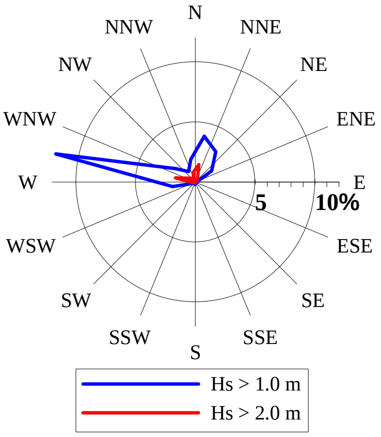

Figure 4. Wave rose of significant wave height for measurements at Lubiatowo buoy station.

Wave groupiness and wave sea direction

Some efforts have been taken to assess the effect of wave direction on the formation of individual extreme waves and group of extreme waves. The analysis was conducted on the basis of data sets recorded at Lubiatowo buoy station in 2001. The exemplary extreme wave shapes and the spectrums corresponding to given record of extreme wave are shown in Fig. 5.

More detailed analysis indicates that the majority of groups of waves containing extreme waves come from the northern direction. On the other hand, the single extreme waves come mainly from the western direction, provided long storm duration. It is also worth noticing, that in each case where the extreme wave occurs, the wave spectrum is multipeaked.

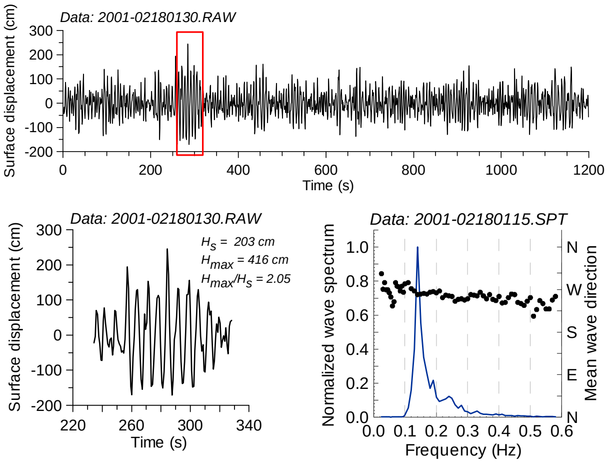

Figure 5. Time series of the sea surface, extreme waves shapes and spectrum.

STATISTICAL ANALYSIS

Statistical methods have been proven to be very useful in the analysis of wind wave records. In the present studies the statistical analysis was carried out for the entire set of data records. Then, more detailed analysis was performed for the Lubiatowo 3-year data sets and next for several selected extreme wave records.

Global statistics for each buoy localization

As it was mentioned before, three sets of the extreme wave records were selected according to the “maximum” wave definition and buoy locations. The relationships between H_{max} and H_s wave heights in the form of a scatter plot, for Lubiatowo is shown in Fig. 6. The strong linear relationship is visible. There are also presented histograms of both maximum and significant heights, illustrating occurrence frequency of such waves.

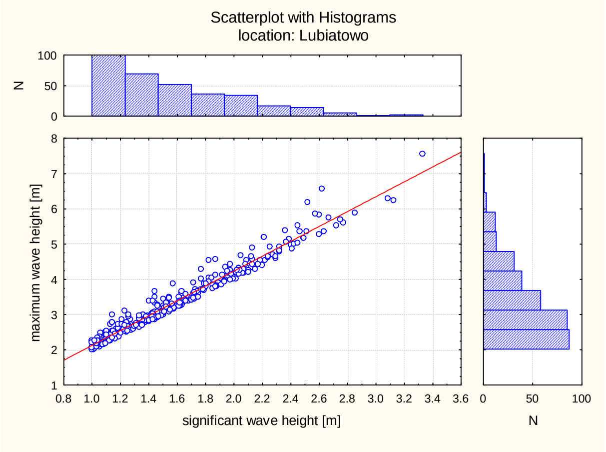

Figure 6. Scatter plot of maximum and significant wave heights and histograms for the entire data set of DWR measurements from Lubiatowo.

An important statistical parameter characterizing random waves is the skewness. The skewness is closely related with wave steepness and is a measure of second-order wave nonlinearities (Stansberg, 1992). The relationship between the statistical skewness and the significant wave steepness for the wave records from Lubiatowo (2000-2002) is shown in Fig. 7. A positive and fairly strong mutual correlation is visible. It is also seen in Fig. 7 that the significant wave steepness of the largest waves exceeds 0.055, which is a typical value for severe strong storms. It should be noted, that although the significant wave steepness has no precise physical meaning, it provides useful information about sea state.

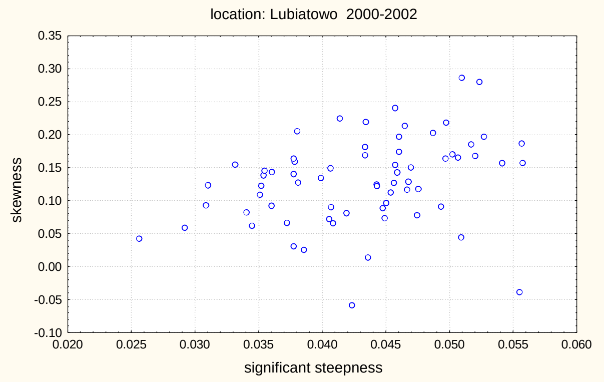

Figure 7. Statistical skewness vs. significant wave steepness for 2000-2002 records from Lubiatowo.

Extreme waves are characterized by both the vertical and horizontal asymmetry. Their crests are usually high and sharp, whereas troughs are rather shallower and wider. A useful parameter describing wave shape is the wave steepness. It was of some interest to analyze differences between the shape of ordinary and extreme waves. An adequate analysis was performed for the one-year set of data from Lubiatowo (2001). This set was chosen because of the greatest number of records. The change of the steepness in relation to the maximum wave height is shown in Fig. 8. The plot in Fig. 8 shows that wave steepness tends to a constant value for severe storms disregarding whether extreme wave was present in the record.

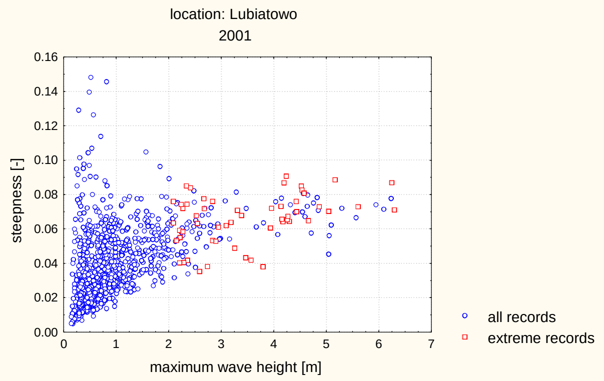

Figure 8. Steepness vs. maximum wave height for records, Lubiatowo 2001.

Statistics of selected records

More detailed statistical analyses were performed for several selected records. For each buoy localization one record (two from Lubiatowo), containing largest value of the maximum wave height and fulfilling extreme wave criteria, was chosen. The records of highest ratio of the maximum and the significant wave heights were also analyzed.

An example of time series of the extreme storm for given buoy location is plotted in the form of wave crest, trough and height envelopes in Figure 9.

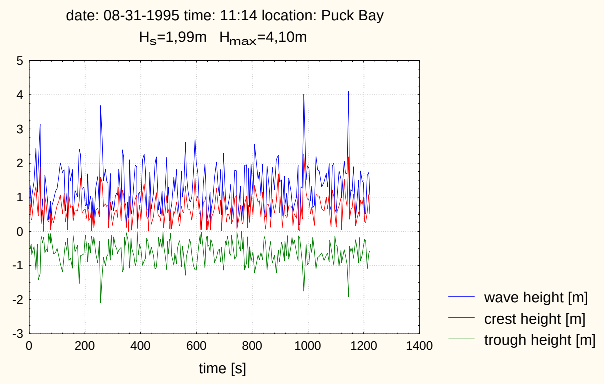

Figure 9. Envelopes of extreme storm record, the Puck Bay 1995.

In general, the water surface can be represented to the first order, as the Gaussian Noise, with a reasonably narrow frequency band. However, real waves show a small but easily noticed departure from the Gaussian surface. The crests are higher and sharper than expected from a summation of sinusoidal waves with random phase, and the troughs are shallower and flatter.

Under the additional assumption that waves are a narrow-band process, it can be concluded that a wave height follows the Rayleigh distribution (Forristall, 1999, Tucker,1991, Ymaguchi, 1996).

However, it may be questionable to estimate extreme wave height from the Rayleigh distribution due to the fact that such wave is a single steep wave and does not follow the narrow-banded Gaussian process.

The comparisons between the observed data and the theoretical Rayleigh-based predictions, in the form of cumulative distributions, are shown in Figure 10a, b. They are given for the selected extreme wave records of data sets from Lubiatowo. Both, group and individual frequency plots were considered (Ott, 1995).

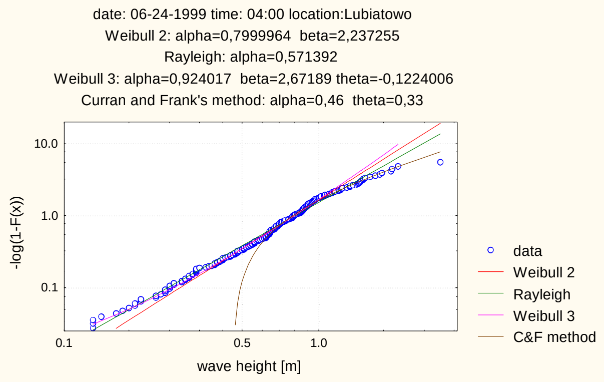

Figure 10a. Individual cumulative distributions of wave heights for different probability models; extreme wave record from Lubiatowo, June 24, 1999.

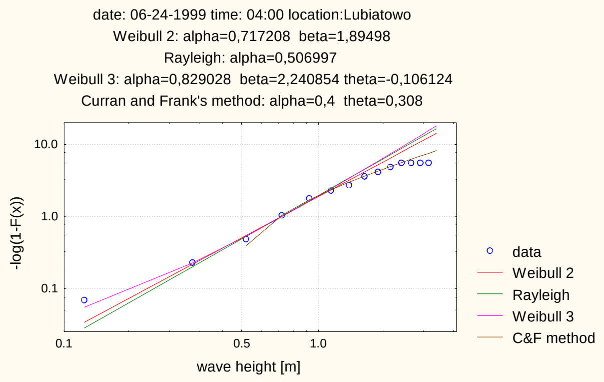

Figure 10b. Grouped cumulative distributions of wave heights for different probability models; extreme wave record from Lubiatowo, June 24, 1999.

A general rule is that there should be at least five observations in any cell of the histogram. If there are less than five observations, the adjacent intervals should be combined to get such a number. In the analyzed extreme wave problem, there are one or few large waves, which form the farthest cell. Combining it with the adjacent cells disturbs the results, because a gap between intervals occurs or the width of the last interval is too large.

It is seen in Fig. 10 that the Rayleigh distribution over predicts extreme wave heights. In other words, the results of statistical analysis show that the occurrence probability of the extreme waves remains below the Rayleigh distribution. This may be partly due to the assumption of a linear, Gaussian narrow-band free-surface.

A better fitting can be obtained using the Weibull distribution (Kondo et al, 1992, Yim and Lai 1996, Ott, 1995), which is in the form that provides more flexibility and variety of shapes than some other models. Both the Weibull 2-parameters and 3-parameters distributions were considered. They were fitted to the selected extreme wave records and the results are also presented in Fig. 10. It is seen that those two probabilistic models, in comparison with the Rayleigh one, provide better approximations of wave height distributions. It is also worth noticing, that the Weibull 2-parameters distribution is more appropriate for high waves than the 3-parameters one.

Although the considered probabilistic models fit quite well to most waves, there is still a significant difference between experimental and predicted values for the extreme waves. Thus, further analysis seems to be necessary and a more adequate model is required to fit the rest of the distribution. For such a “tail-fits”, the two parameter exponential model can be used (Ott, 1995).

The tail exponential fitting, together with previously considered the Rayleigh and the Weibull distributions, are shown in Fig. 10a-b. It is seen in the Fig. 10, that although tail exponential model differs considerably from the experimental points for small to moderate wave heights, it provides fairly good fitting for high waves. Thus, the proposed approach seems to be more suitable for the statistical analysis of extreme wave distributions.

Because the probability distribution of the period of individual waves depends on the heights of the waves, it is necessary to study the joint statistics of wave height and period (Tucker, 1991, Tayfun, 1990). The required result from such a study is the expected period of the highest waves. Based on bivariate histograms for the selected extreme wave records, the ratio of the periods of highest individual waves and mean period appeared to be in the range of 1.83 – 2.03. The periods of the highest waves for the Puck Bay and Niechorze are close to each other and are equal to about 5.5 s. The period of extreme wave has the highest value for the extreme wave record from Lubiatowo and equals 8 s, while the longest period exceeds 13 s.

LONG RECORD FROM THE PUCK BAY

The unique, continues data set comprising 245 typical 20-minutes records have been analyzed. The storm occurred in the Puck Bay in 1995 and lasted more than 3 days. The significant wave height H_s was more than 1 m and the maximum wave height exceeded 5 m. The time series representing variation of the maximum and significant wave heights assigned to each record are shown in Fig. 11. The significant wave height computed for the whole storm is also presented. It is seen in Fig. 11 that the storm is highly non-stationary. One should realize that typical statistical analyses are conducted on 20-minutes records, which are assumed to be stationary.

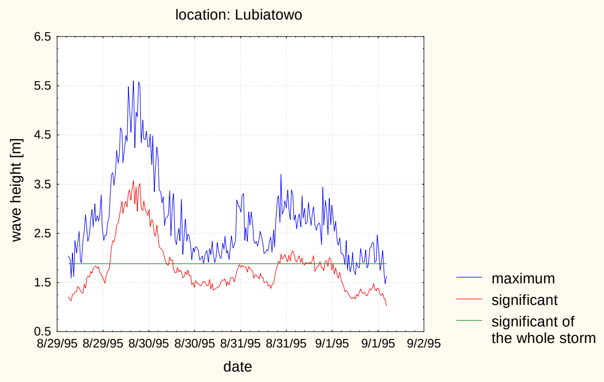

Figure 11. Time series of the maximum and significant wave heights for the long storm in the Puck Bay, 1995.

The available unique data set was analyzed by applying an extreme-value approach. The histogram of the maximum wave heights with an extreme-value distribution fitting was applied. This distribution can be obtained by considering extreme waves coming from all 20-minutes records. However, the results showed some discrepancies between theoretical and observed distribution. Much better fitting was obtained for the ratio of the maximum to significant wave heights. Corresponding histogram is shown in Fig. 12. The goodness-of-fitting is illustrated on the so call p-p graph in Fig. 13, where the observed cumulative distribution is plotted against a theoretical cumulative distribution function. A high accuracy of fitting is clearly visible.

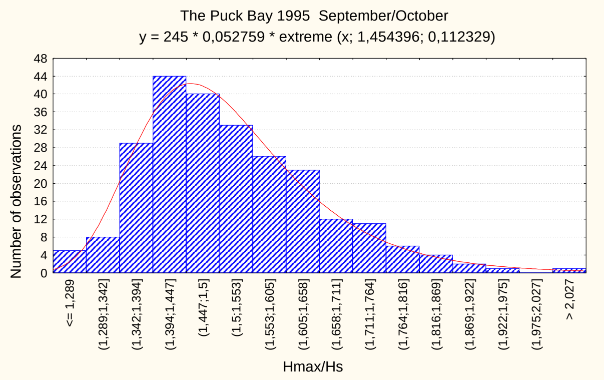

Figure 12. Histogram of the ratio of the maximum to significant wave heights and extreme-value distribution fitting.

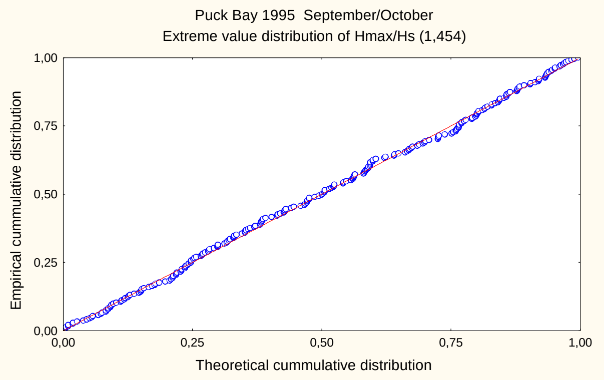

Figure 13. Probability-probability plot for the ratio of maximum to significant wave heights for the extreme-value distribution.

WAVELET TRANSFORM ANALYSIS

The occurrence of extreme waves or extreme wave groups is often a highly non-stationary phenomenon. In order to investigate the structure of such waves, a proper method to analyze the temporal and spectral characteristics is required. Most commonly used method for spectral analysis i.e. Fourier transform is inappropriate for studying non-stationary signals. The wavelet transform method has been proven to be an efficient tool in the analysis of extreme waves and extreme wave events. The method provides the wave energy distribution and enables to localize it simultaneously in time and frequency domain (Chien et al, 2002).

The wavelet transform method was applied to analyze several data sets recorded at Lubiatowo in 2001. The results are presented in Fig. 14a, b. In particular, in Fig. 14a the results of the analysis of a record with extreme wave group are presented. The results of the analysis of an extreme wave record with bimodal spectral data are presented in Fig. 14b. The plots in Fig. 14a, b show that the wavelet transform method fairly well detects extreme waves and extreme wave groups.

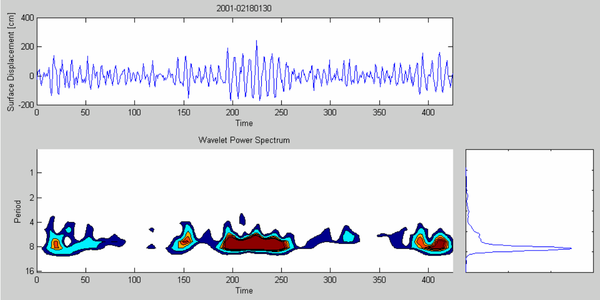

Fig. 14a. Wavelet Transform analysis of MAXWAVE record for Lubiatowo, 2001 February, 18.

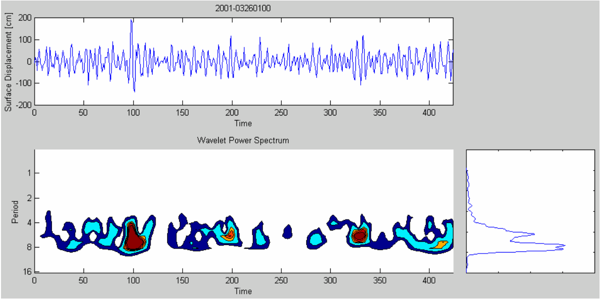

Fig. 14b Wavelet Transform analysis of MAXWAVE record for Lubiatowo, 2001 March, 26.

CONCLUSIONS

1. The analysis of available wave records from the southern Baltic Sea revealed a large number of extreme wave and wave events. The maximum significant wave height was about 4 m. The highest recorded wave was about 7.6 m.
2. The formation of individual extreme waves and wave groups is effected by storm direction and duration. A preliminary analysis indicates that extreme wave groups come from the northern direction whereas extreme wave events occurs mainly in the storms coming from the western direction.
3. The wavelet transform method has been proven to be an efficient tool in the analysis of extreme waves and extreme wave events. The wavelet transform method fairly well detects extreme waves and extreme wave groups.
4. The steepness of the extreme waves does not differ significantly from the steepness of other large waves. The steepness can be even higher for waves of moderate length and tends to a constant for extreme waves.
5. A positive and fairly strong mutual correlation is observed between the statistical skewness and the significant wave steepness. No distinct relations between kurtosis and other wave parameters were found in the analyzed wave records.
6. The Rayleigh distribution overpredicts extreme wave heights. A better fitting can be obtained using the Weibull distributions. The Weibull 2-parameters distribution is more appropriate for high waves than the Weibull 3-parameters one. In some cases, the two parameters tail exponential model provides fairly good fitting for high waves.

7. The extreme-value distribution fits well extreme wave heights coming from a set of continuous storm records, although much better fitting can be obtained for the ratio of the maximum to the significant wave heights. The Weibull distribution cannot be used in such case.

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