Trends and extremes of wave fields in the north–eastern part of the Baltic Proper*

OCEANOLOGIA, 48 (S), 2006.
pp. 165–184.

KEYWORDS
Wind waves
Baltic Sea
Wave climate
Wave measurements

Barry Broman[1]
Thomas Hammarklint[2]
Kalev Rannat[3]
Tarmo Soomere[3,*]
Ain Valdmann[4]

[1] Swedish Meteorological and Hydrological Institute,
Rossby Centre,
Folkborgsvägen 1, SE–60176 Norrköping, Sweden

[2] Swedish Meteorological and Hydrological Institute,
Observation Unit,
Folkborgsvägen 1, SE–60176 Norrköping, Sweden

[3] Centre for Non-linear Studies,
Institute of Cybernetics,
Tallinn University of Technology,
Akadeemia tee 21, EE–12618 Tallinn, Estonia;

e-mail: soomere@cs.ioc.ee

* corresponding author

[4] Municipal Engineering Services Department, City of Tallinn,
Mündi 2, EE–15197 Tallinn, Estonia

Received 31 November 2005, revised 12 June 2006, accepted 16 June 2006.

* This work was supported by the Estonian Science Foundation (grant No 5762). The study was partially carried out when one of the authors (TS) was visiting the Centre of Mathematics for Applications, University of Oslo, within the framework of the Marie Curie Transfer of Knowledge project CENS-CMA (MC-TK-013909).

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

Abstract

The paper analyses one of the longest contemporary wave measurements in the northern Baltic Sea, performed at Almagrundet 1978–2003. This record contains the roughest instrumentally measured wave conditions (significant wave height = c. 7.8 m) in the northern Baltic Proper until December 2004. The data for the years 1979–95, the period for which the data are the most reliable, show a linear rising trend of 1.8% per annum in the average wave height. The seasonal variation in wave activity follows the variation in wind speed. The monthly mean significant wave height varies from 0.5 m in May–July to 1.3–1.4 m in December–January. No corrections have been made in the analysis to compensate for missing values, for their uneven distribution, or for ice cover.

1. Introduction

The exceptional storm named Erwin/Gudrun of January 2005 highlighted an inadequate awareness of extreme wave properties (Soomere et al. 2006) and of the height and spatial extent of extreme water level conditions (Suursaar et al. 2006) under existing climatological conditions. This event motivated studies of existing long-term wave measurements in the area in question.

Wave observations in the Baltic Sea area extend back more than 200 years. For example, records of hydrometeorological parameters at Tallinn Harbour, started in 1805, optionally contained visually estimated wave parameters (R. Vahter, personal communication 2003). These data, however, represent only wave properties in the near-coastal regions and often inadequately reflect open-sea wave fields (Orlenko 1984).

Contemporary wave measurements in the northern Baltic Sea were launched about three decades ago when several semi-autonomous measurement devices were deployed in different parts of the sea. In particular, bottom-fixed devices were installed and operated by the Swedish Meteorological and Hydrological Institute (SMHI) near the caisson lighthouse of Almagrundet (located in the eastern sector of the northern Baltic Proper, 59°09′N, 19°08′E, Fig. 1). The wave data from this site form the main object of study in this paper. An analogous device was installed at Ölands södra grund (south of Öland) in 1978, as was an accompanying waverider buoy near Hoburg, south of Gotland. This was done within the framework of studies of the technical and economical possibilities of wave power plants in Swedish waters (Mårtensson & Bergdahl 1987).

An important step towards understanding open-sea wave conditions in the northern Baltic Proper (NBP) was made when the Finnish Marine Research Institute deployed a state-of-the-art directional waverider there at a depth of about 100 m (Fig. 1, 59°15′N, 21°00′E). The relevant data set now covers 10 years, starting from September 1996 but excluding ice

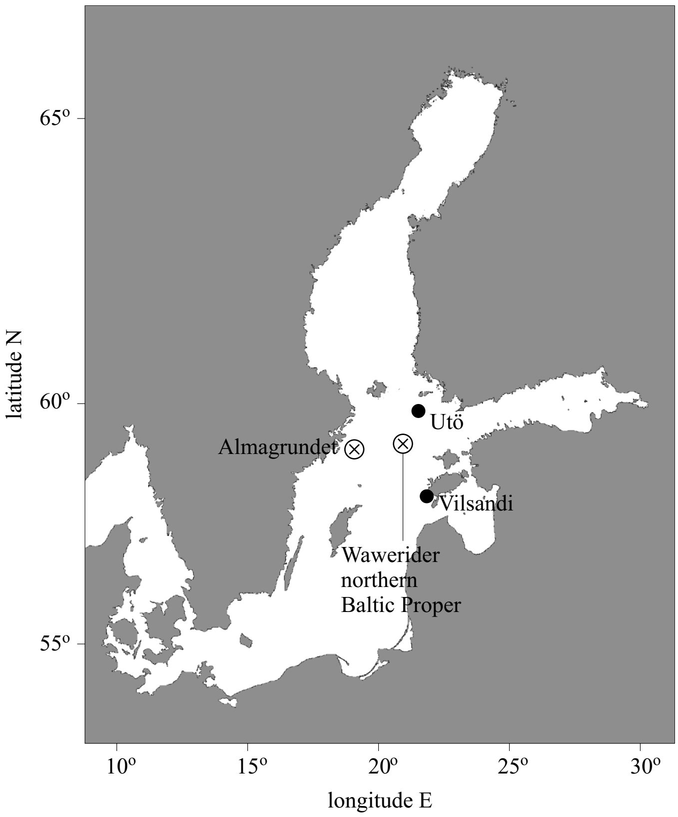


Fig. 1. The location of the wave measurement sites at Almagrundet and in the northern Baltic Proper, and the wind measurement sites at Vilsandi and at Utö

seasons. For a description and preliminary analysis of the data, see Kahma et al. (2003).

High-quality wave data sets have been obtained in the areas around Finland since the 1970s (Kahma et al. 1983). Some of these sets contain directional wave information (Kahma & Pettersson 1993, Pettersson 1994, Pettersson 2001, Kahma et al. 2003) that was not recorded in the Almagrundet data. This data has considerably modified our awareness of extreme wave conditions in the semi-enclosed sub-basins of the Baltic Sea. For example, until a value of $H_S = 5.2$ m was recorded in November 2001 (Pettersson & Boman 2002), experts had generally agreed that the significant wave height should not normally exceed 4 m in the central part of the Gulf of Finland.

The significant wave height H_S is approximately equal to the average height $H_{1/3}$ of the highest 1/3 of all the waves during a certain time interval. In contemporary wave measurement devices and in numerical wave models it is estimated directly from the (directionally integrated or non-directional) wave energy spectrum as

$$H_S = 4\sqrt{m_0}, \tag{1}$$

where m_0 is the zero-order moment of the wave spectrum (correspondingly, the total variance of the water surface displacement time series).

Unfortunately, hardly any instrumentally measured wave data are available from the coastal areas of Estonia, Latvia and Lithuania, except for visual observations from the coast and for sporadic measurements made with pressure-based sensors (Soomere 2005). This makes it virtually impossible to identify basic features of the spatial distribution of wave properties in the Baltic Proper from the measured data. This gap has been partially filled by the use of numerical models that adequately represent the sea state of the northern Baltic Sea even in extreme conditions (Jönsson et al. 2002, 2005, Soomere et al. 2006). The overall picture of wave activity follows the well-known anisotropy of the wind and wave regime in the Baltic Proper (Mietus 1998, Soomere 2003). Statistically, the regions of the largest wind wave activity are found along the eastern coasts of the Baltic Proper.

To complete this overview of existing knowledge, mention should be made of several numerical wave studies performed for the southern part of the Baltic Sea (e.g. Gayer et al. 1995, Paplińska 1999, Blomgren et al. 2001) or for limited areas of the northern Baltic Proper (Soomere 2003). A number of wave studies have focused on specific problems of Baltic Sea wave fields, such as the frequent occurrence of multi-peaked wave spectra (Kahma 1981), possible changes in the wave climate caused by changes in storminess (WASA Group 1995), methods of estimating the wave climate (Mietus & von Storch 1997), the persistence of wave statistics (Boukhanovsky et al. 1999), wave fields in slanted fetch conditions (Kahma & Pettersson 1994, Pettersson 2004), and the wave climate in small semi-enclosed basins (Soomere 2005). Valuable wave data can also be found in books published in the former USSR (Davidan et al. 1978, 1985).

The pattern of dominant winds and the geometry of the Baltic Proper suggest that the highest and longest waves appear to occur near the entrance to the Gulf of Finland and off the coasts of Saaremaa, Hiiumaa and Latvia (Jönsson et al. 2002, 2005, Kahma et al. 2003, and Soomere et al. 2006, among others). This feature has caused some discussion about whether the Almagrundet wave data correctly represent open-sea wave conditions (Kahma et al. 2003). Almagrundet is fully open to the east and south–south–east, but the fetch length for the dominant winds from the south-east and possibly north (Mietus 1998, Soomere & Keevallik 2001) is quite limited. Measurements at this site may therefore give a somewhat biased picture of wave properties in the northern Baltic Proper.

Nonetheless, the Almagrundet wave data constitute one of the most valuable data sets for the Baltic Sea. The wave measurement devices at the site have been active during a quarter of a century (1978–2003). Hence, the data set is one of the longest instrumentally registered time series of wave properties in the Baltic Sea area. It contains the highest ever recorded significant wave height ($H_{1/3}$ = 7.8 m, estimated from the 10th highest wave, assuming Rayleigh distributed wave heights, H_S = 7.3 m estimated from the wave spectrum) and the highest single wave (12.75 m, both filed in January 1984) until a comparable significant wave height and an even higher single wave were recorded in the NBP in December 2004. The actual possibility of extremely severe wave conditions at this site confirms that the data are particularly valuable for understanding the behaviour of wave fields in the Baltic Sea. Note that some sources (e.g. Kahma et al. 2003) mention the value H_S = 7.7 m as the highest in the Almagrundet data. This probably reflects a certain ambiguity in significant wave height estimates from different approximations of the observed parameters of the complex wave fields. Although there is some evidence that the significant wave height reached 10 m in some other areas of the Baltic Sea in January 2005 (Soomere et al. 2006) and that H_S = 7.7 m was registered in the NBP in December 2004, the formal record of the highest significant wave height from Almagrundet has not been exceeded.

A small part of the Almagrundet data has been discussed in conference papers and local reports (e.g. Svensson 1984, Mårtensson & Bergdahl 1987 and references therein). Some excerpts from this data set have been used elsewhere (e.g. Kahma et al. 2003). However, a comprehensive analysis of this longest contemporary wave measurement activity in the northern Baltic Sea area has yet to be undertaken. The current paper is directed towards filling this gap. Its main purpose is to analyse the typical and extreme wave conditions at this site and to identify overall trends in the wave activity. It begins by describing the measurement site, apparatus and measurement routine. The wave height distribution and the joint distribution of wave heights and periods (scatter diagram) are then presented, and the reliability of the wave data is discussed at length. Extreme wave conditions, seasonal and interannual variations in the wave field are also discussed. The results presented here were obtained exclusively from the measured data, that is, Type A statistics in terms of the classification of Kahma et al. (2003); no corrections have been made to compensate for missing values, for the uneven distribution of data, or for ice cover.

2. Measurement devices, procedure and data

Almagrundet is a shoaling area about 10 nautical miles south–east of Sandhamn in the Stockholm archipelago. The name refers to a Norwegian sailing ship that ran aground in the area in 1866. The first lightship, showing the inlet to Sandhamnsleden, was located here in 1896. Many lightships followed, until the caisson lighthouse of today (Fig. 2) became operative in 1965. Since it is 30 m tall and stands in a 14 m deep area not sheltered by the mainland, it is an attractive location for hydrometeorological measurements. Since 1974 there have been meteorological and oceanographic sensors on the caisson. Over the years such data as wind speeds and directions, air and water temperatures, currents and waves have been measured.

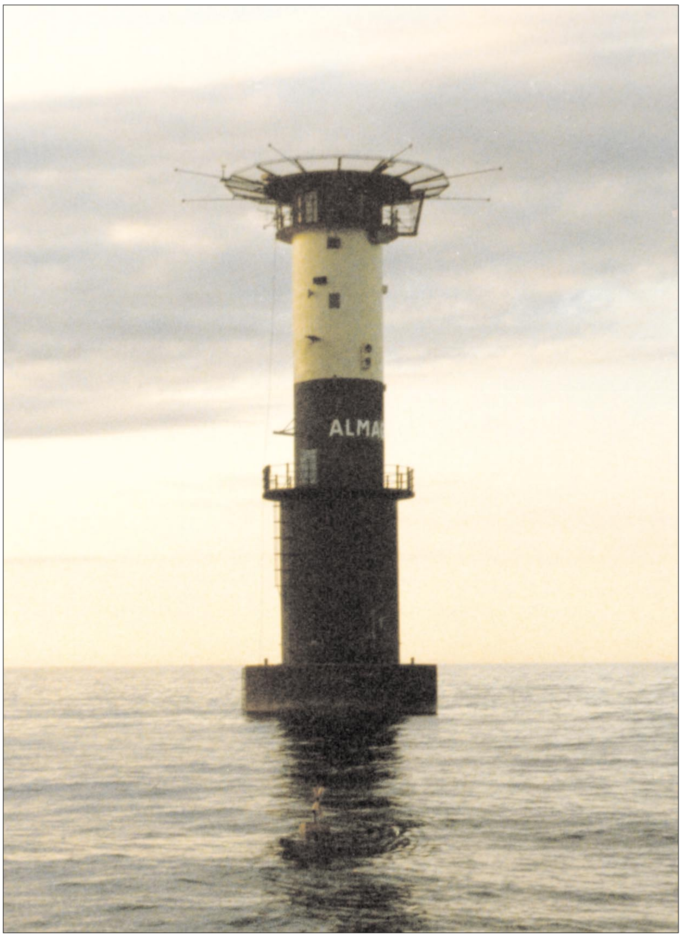


Fig. 2. A view of the Almagrundet lighthouse. Photo: SMHI

An inverted echo-sounder from SimRad was placed at a depth of about 30 m at about 100 m from the lighthouse in 1978 and was active until 1995. Some sources report slightly different values for the water depth at this location; for example, one diving report gives 24 m and some other reports mention 29 m. An analogous device (WHM) was installed in a neighbouring location at a depth of 29 m; it was in operation from 1 January 1992 until 2003. The two devices were operated in parallel during three and a half years, until mid-September 1995. Such an overlap makes it possible to cross-check the data sets from different devices. An overview of the devices, the measurement procedure and the method of calculating wave properties from the raw data during the first years (1978–1980/81) of measurements at Almagrundet are presented by Mårtensson & Bergdahl (1987).

The record of the physical position of the water surface is sampled with a frequency of 10 Hz during 640 seconds (approximately 11 minutes) each hour. The record is first filtered with the use of a low-pass filter with a cut-off frequency at 0.67 Hz, thus wave components with periods of less than 1.5 s are filtered out. The data then passes a plausibility test: the difference between any two successive samples is not allowed to exceed a certain value. This value is automatically adjusted to existing sea conditions based on the knowledge of the wave period and how steep the wave can be. By doing this, the interference of waves from various sources, breaking waves, and possibly very steep waves can be discarded. An averaging procedure over 5 consecutive samples follows, which results in a time series of the position of the water surface twice a second. This procedure is consistent with the above-mentioned filtering of the raw data.

The spectral analysis of this time series is split into ten steps, each involving the analysis of 128 values of the water surface position from a time slice of 64 s. The wave spectrum over a full measurement interval of 1280 samples is computed as the average of 10 spectra from the time slices. Mårtensson & Bergdahl (1987) claim that this method gives a good spectral estimate, which is usually better than the one directly obtained with the use of 1280 samples. The spectra are computed for a discrete set of frequencies 5/64–42/64 s^{-1}, with a step of 1/64 s^{-1}; this is equivalent to a period range of 12.8–1.5 s. For the highest frequencies only the mean energy of spectral bins 33/64–37/64 s^{-1} and 38/64–42/64 s^{-1} is stored. The frequency range was extended to 1/64 Hz (corresponding to waves with a maximum period of 64 s) as of 1 October 1983.

An important feature of the measurements in question is that the largest waves, the mean period, and the wave height are registered with the use of the classic zero-downcrossing method (IAHR 1989). An estimate of $H_{1/3}$ is calculated assuming that wave heights are Rayleigh distributed:

$$H_{1/3} = \frac{H_{10}}{\sqrt{\frac{1}{2}\ln\frac{N}{10}}}, \tag{2}$$

where H_{10} is the 10th highest wave and N is the total number of waves. Although the 10 largest waves are detected, only the 5 largest are stored.

There are 95 458 single measurements in the SimRad data set used in this study. Several records are clearly erroneous and have thus been omitted from further analysis. The remaining records describe the evolution of wave properties in a reasonable manner (see Fig. 6, p. 176), and the data set is probably reliable.

The WHM data set contains 50 532 records. The data from the beginning of 1992 until July 1992 are completely unrealistic and have been excluded from the analysis. The remaining set contains 46 671 single measurements. As in the SimRad data, several single records are clearly incorrect and have also been omitted from further analysis.

There are 6619 simultaneous wave height measurements made by both devices. The WHM data give a mean wave height that is 7.54 cm (about 5%) larger than the data recorded by the SimRad equipment, whereas the root-mean-square difference between wave heights is 29 cm. This is an acceptable scatter, because the devices were located at some distance from each other.

Formally, the mean period over the full set of simultaneous measurements given by the SimRad is 2 s longer than that of the WHM. The root-mean-square difference in period estimates is larger, c. 3 s. This large difference suggests that either different definitions of the wave period were used in the measurements with the different devices or at least one of the devices was malfunctioning. The periods recorded by the SimRad follow the wave heights in a sensible manner (see Fig. 6, p. 176), whereas the periods recorded by WHM are mostly locked at around 4 s (see Fig. 7, p. 177). This comparison suggests that there may have been some problems with the WHM equipment during certain time intervals. For that reason, the wave periods recorded by the WHM device will not be considered in the analysis below.

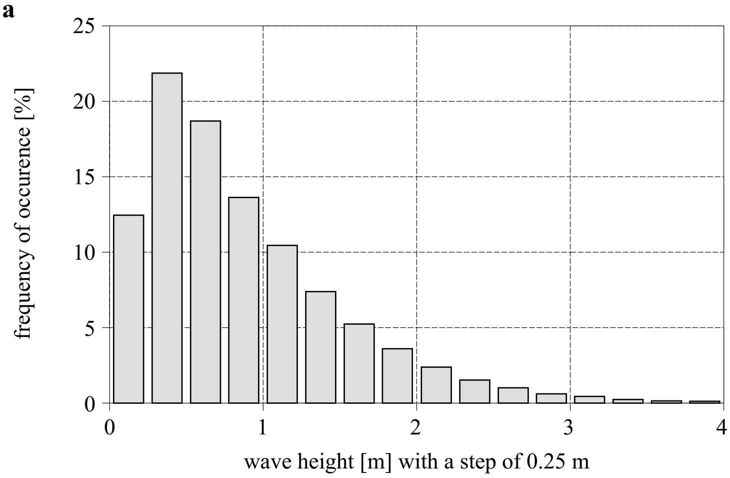
It should be emphasised that the values of the wave height $H_{1/3}$ in the WHM data also seem to be generally less reliable than those in the SimRad data. The WHM wave height time series occasionally contains a large number of relatively modest but still evidently unrealistic peaks (see Fig. 7, p. 177). Yet the overall behaviour of the measured wave height $H_{1/3}$ apparently follows the realistic sea state. For this reason the conclusions below are based mostly on the SimRad data, whereas the WHM recordings are considered to be merely indicative.

3. Main properties of the wave climate

According to the SimRad data the mean wave height $H_{1/3}$ at Almagrundet between 1978 and 1995 is 0.876 m. The median wave height is 0.7 m and the most frequent wave conditions correspond to $H_{1/3} = 0.25$–0.375 m. The frequency of occurrence of different wave heights is presented in Fig. 3.

The WHM wave data show somewhat more intense wave activity. The mean wave height over the whole measurement cycle of this device (1993 –2003) is 1.04 m. The wave height median is 0.73 m, that is, practically the same as for the SimRad data.

a



b

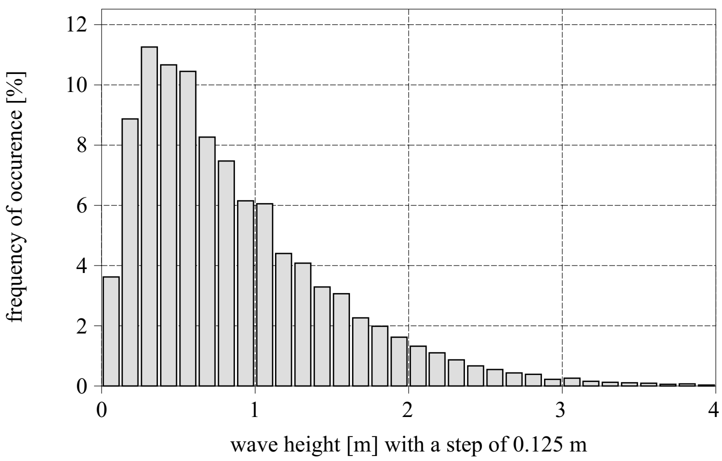
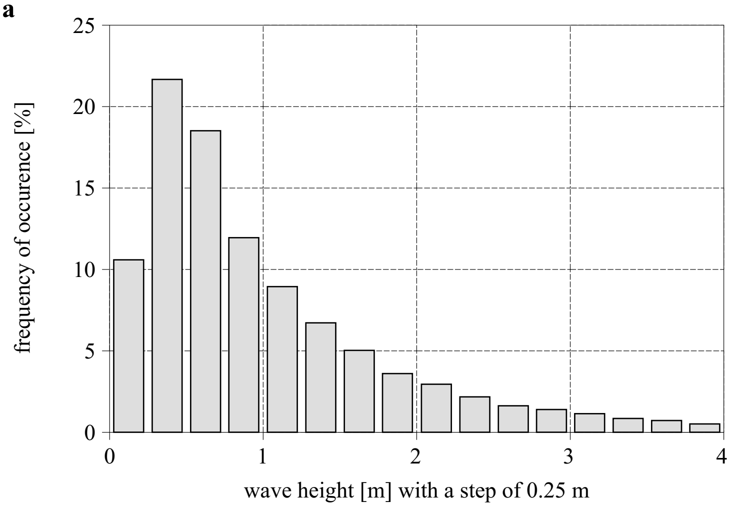


Fig. 3. Frequency of occurrence of wave heights at Almagrundet 1978–95 according to the SimRad wave data 1978–96 for wave height steps of 0.25 m (a) and 0.125 m (b)

The wave height statistics from the WHM data (Fig. 4) are very close to those obtained from the SimRad data for the most common wave heights of 0.25–1 m. The largest differences are for practically calm situations ($H_{1/3} < 0.25$ m), the frequency of which is clearly smaller in the WHM data than in the SimRad data. The larger proportion of sea states with $H_{1/3} > 1$ m in the WHM data suggests that this equipment either tends to overestimate wave heights in relatively rough seas or that the data in question contain some portion of unrealistic values.

a



b

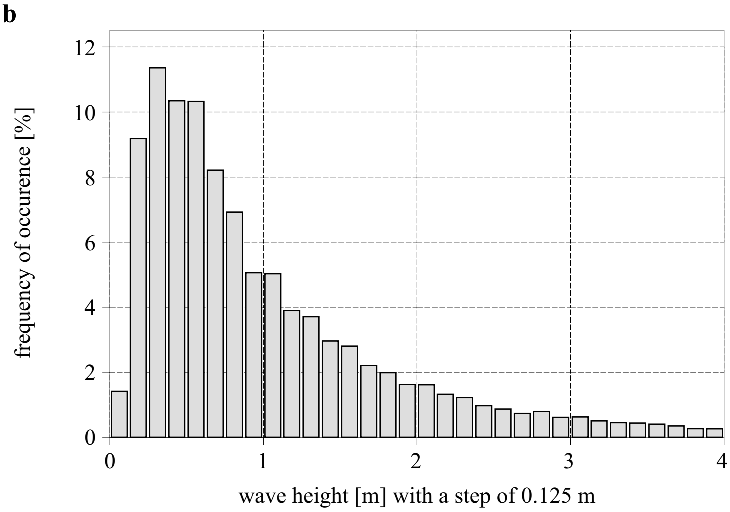


Fig. 4. Frequency of occurrence of wave heights at Almagrundet 1993–2003 according to the WHM wave data 1993–2003 for wave height steps of 0.25 m (a) and 0.125 m (b)

Seas with $H_{1/3} \geq 4$ m have occurred about 400 times during the period in question, that is, such wave conditions occur with a probability of about 0.42% or, on average, during about 20 hours each year. The storms causing such high waves, however, usually occur several times a year, each lasting a few hours.

The shape of the plot of the number of records of different wave heights $H_{1/3}$ and mean periods (Fig. 5) is typical of Baltic Sea conditions (see Kahma et al. 2003). The typical mean wave periods are 4–5 s for wave heights below 1 m, about 6 s for wave heights around 2 m, and exceed 7 s only when wave heights are 3 m or higher.

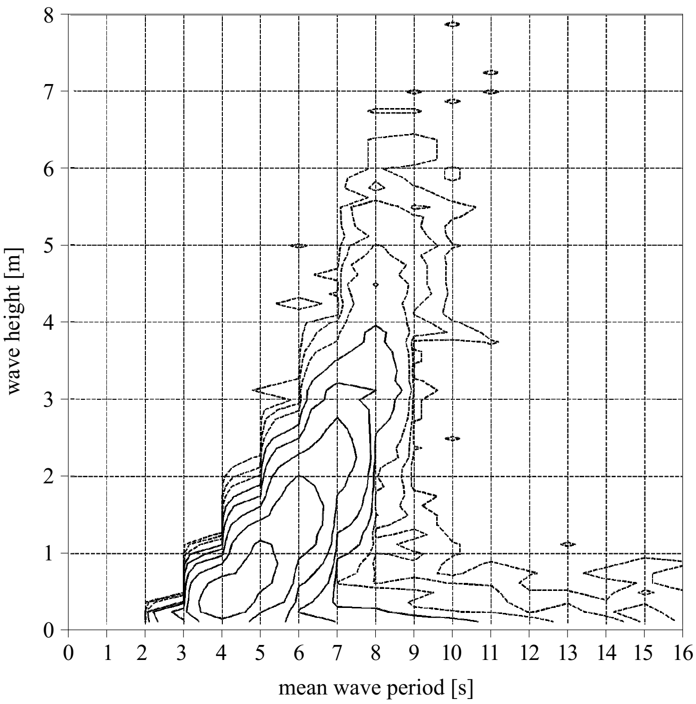


Fig. 5. Scatter diagram of wave heights $H_{1/3}$ and mean periods in the SimRad data. The wave height step is 0.125 m. The range of periods is shown on the horizontal axis: for example, 2 s stands for $T_z < 2.5$ s, 3 s stands for $2.5 \leq T_z < 3.5$ s etc. Isolines for 1, 3, 10, 33, 100, 330, 1000 and 3300 cases are plotted, whereas isolines for 1–10 cases are dashed lines

Note that the data set in question contains the mean period. The corresponding values of the mean period, found from the recorded wave spectra, are about 20% larger than the peak period; however, not all spectra have clearly defined peak.

In a certain number of situations long waves with periods over 10 s dominate in the wave field. This usually happens in the case of swell-dominated low wave conditions when the wave height $H_{1/3}$ is well below 1 m. Very large mean periods may also occur during extremely rough seas. For example, the mean period reached 11 s in one case of rough seas with $H_{1/3}$ around 4 m, and also in the final stage of the January 1984 storm, when waves with periods 11 s dominated the wave field with $H_{1/3}$ about 7 m.

4. Extreme wave conditions

The most violent storm recorded by the SimRad device occurred in January 1984. The wave data from this storm were used in the description of wave statistics in Kahma et al. (2003). The wave height $H_{1/3}$ was very close to or exceeded 6 m during 10 hours that night. In the late evening of 13 January (23:00 GMT, i.e. 01:00 hrs local time on 14.01.1984) the wave height $H_{1/3}$, estimated from the 10th largest wave, reached 7.82 m (Fig. 6). This is the highest experimentally measured wave height in the northern Baltic Sea to date. The significant wave height, calculated directly from the SimRad wave spectrum, is somewhat smaller – $H_S = 7.28 \approx 7.3$ m at the storm maximum.

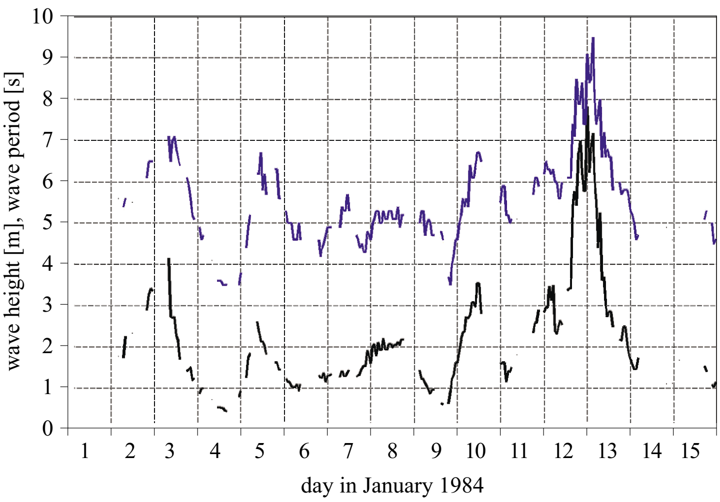


Fig. 6. The wave height $H_{1/3}$ (lower line) and the mean period (upper line) at Almagrundet in January 1984 according to the SimRad data. Note the large numbers of gaps in the lines, which correspond to the missing data

The wave periods during the storm in question remained fairly modest. When the maximum wave height occurred, the mean wave period was 9.1 s and the peak period was 10.7 s. Both periods are considerably smaller compared with the wave periods in the roughest seas measured in the NBP (12 s, Kahma et al. 2003) or with those that occurred in the eastern part of the NBP in January 2005 (about 11–12 s measured in the NBP, about 13 s forecast in the eastern part of the sea (Soomere et al. 2006).

The SimRad data set contains one more case when the significant wave height at Almagrundet was close to 7 m. A severe storm occurred on 30 January 1988 when the wave height was close to or exceeded 6 m and reached $H_{1/3} = 6.73$ m at 04:00 GMT. Since Almagrundet is somewhat sheltered, the significant wave height in the open part of the northern Baltic Proper could theoretically have reached 7 m during this storm.

Other extreme wave storm events in the northern Baltic Proper reflected in the wave data from Bogskär and by the waverider buoy in the central part of the NBP are not so significant in the Almagrundet data. Kahma et al. (2003) report that three very strong wave storms took place in the 1990s. There are no reliable wave data at all in the Almagrundet data set from the severe storm in January 1993. The maximum wave height during two extremely violent storms in December 1999 (when the significant wave height in the NBP exceeded 7 m, Kahma et al. 2003) was about 6 m at Almagrundet. This is still quite high for this somewhat sheltered site.

There are several candidates in the WHM data set for the highest significant wave height and for the highest single wave. However, closer examination shows that the relevant records are probably erroneous.

The highest formally recorded wave height in the WHM data occurred on 25–26 March 1997 (Fig. 7). The wave height $H_{1/3}$, estimated from the

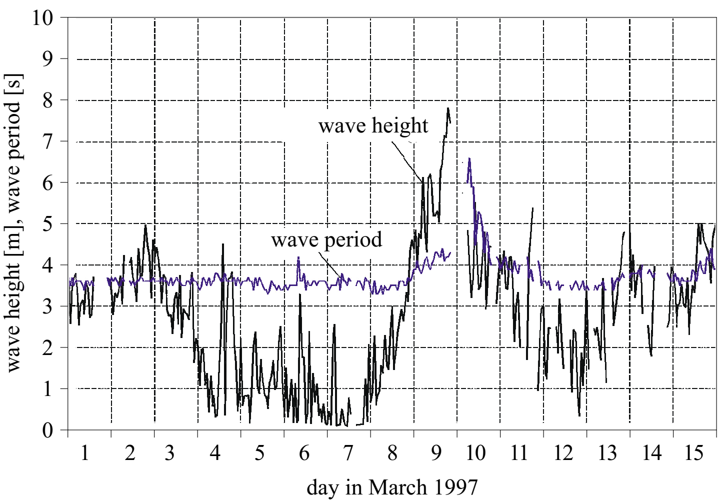


Fig. 7. The wave height $H_{1/3}$ and the mean period at Almagrundet in March 1997 according to the WHM data

10th highest wave, reached 7.83 m during a severe, long-lasting storm, which affected nearly the whole of the Baltic Proper. The maximum wind speed at Utö was 22 m s^{-1} and at Vilsandi 19 m s^{-1} during this event. On the Estonian coast, the storm winds were blowing from the south, and so were capable of exciting high waves at Almagrundet. Yet the significant wave height, estimated from the wave spectrum, was 5.7 m and the highest single wave reached 10.24 m. Therefore, although this was certainly a case of severe seas, the above-mentioned value of 7.83 m is either incorrect or only reflects the situation when a group of large waves occurred during a certain measurement interval.

An extremely high single wave with a height of 12.79 m is present in the WHM wave data on 25 December 1996 at 03:00 GMT. The significant wave height, estimated from the 10th highest wave, was 6.37 m during this measurement interval, thus formally supporting the possibility of that single high wave occurring. There was a fierce, long-lasting north-easterly storm on the sea, with wind speeds up to 21 m s^{-1} at Utö, and thus favourable conditions existed for the occurrence of high waves at Almagrundet. Still another feature suggesting that this record is most probably incorrect is that the significant wave height, estimated from the wave spectrum, was only 3.8 m.

5. Annual and interannual variation of the wave conditions

An extremely important question is whether the data set in question reveals any long-term changes in the wave activity in the Baltic Proper. The total coverage of the measurements is about 25 years, which is usually long enough to extract basic long-term trends. Fig. 8 presents the annual mean wave height measured by both devices at Almagrundet over the whole measurement period together with the percentage of available (i.e. successful) measurements in each year.

The measurements with the SimRad equipment started on 27 October 1978 and cover only 14% of the calendar year 1978. Since the late autumn and early winter months are the windiest and wave conditions are then usually the most severe (Mietus 1998, Kahma et al. 2003), the average wave height for this year $H_{1/3} = 1.12$ m is apparently overestimated. For this reason, data from this year have been ignored in estimates of the long-term trends; they are included, however, in the following analysis of seasonal variability.

The SimRad data for the years 1979–95 show a linear rising trend of 1.8% per annum in the average wave height. The correlation coefficient between the trend line and the measured wave data is about 0.66. Such a trend follows the general tendency of the wind speed to increase over

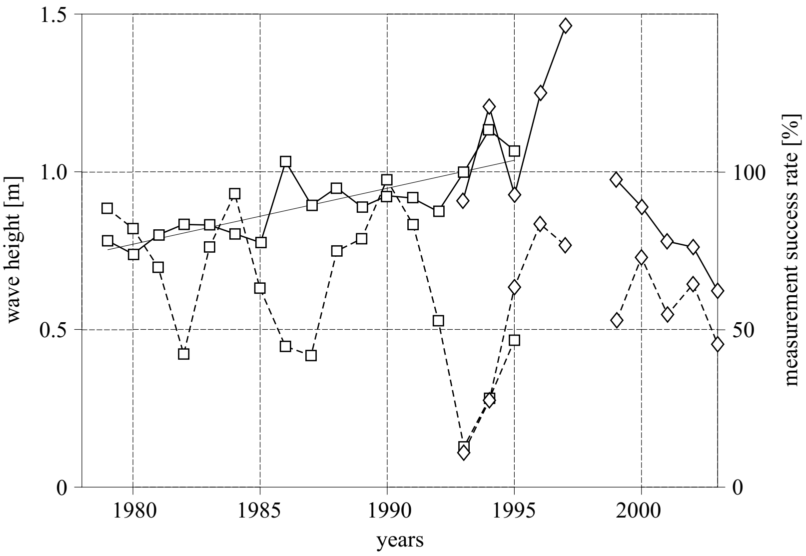


Fig. 8. The annual mean wave height $H_{1/3}$ measured by the SimRad equipment (squares on solid line), the relevant trend line for the years 1979–95, and the wave height measured by the WHM equipment (diamonds on solid line). The measurement success rate (squares and diamonds on dashed lines) is the percentage of acceptable measurements within a particular year

the northern Baltic Sea (see below). The increase in wave heights at Almagrundet, however, is much more intense than analogous trends for the southern Baltic Sea or for the North Sea, which are estimated at less than 1% per year (Gulev & Hasse 1999, Vikebo et al. 2003). Yet it is comparable with the analogous trend reported by Bacon & Carter (1991) for the North Atlantic.

Comparison of annual mean wave heights with the percentage of available measurements (Fig. 8) suggests that the variation in the number of successful measurements during a specific year may not affect this trend. There are several reasons why wave data are missing. For example, it is plainly pointless to attempt wave measurements when the sea surface is ice-bound. Many years have a data coverage of c. 90%. There are prolonged periods in 1982, 1986, 1987 and 1992–94 when the instrumentation failed to produce data. The gaps in the 1980s occur mostly during winter and early spring, and most of them are apparently caused by the presence of sea ice. In 1990s the failures occur more regularly; only c. 12% of the measurements for 1993 exist in the data set. The lack of a lot of data from these years is apparently caused by the failure of data flow during certain time intervals. Yet a fairly steep rising trend in wave height by c. 1.3% per annum can be inferred from the data of 1979–92.

There is an evident match in the temporal behaviour of the Utö wind data (Fig. 9) and the SimRad wave data. The wind data from this small island in the northern Baltic Proper (Fig. 1) well represents wind conditions in the NBP (Soomere 2003, Kahma et al. 2003). This match can be traced even in years poorly covered by measurements and suggests that the increase in the annual mean height at Almagrundet is a part of the long-term changes in the hydrometeorological conditions in the Baltic Sea.

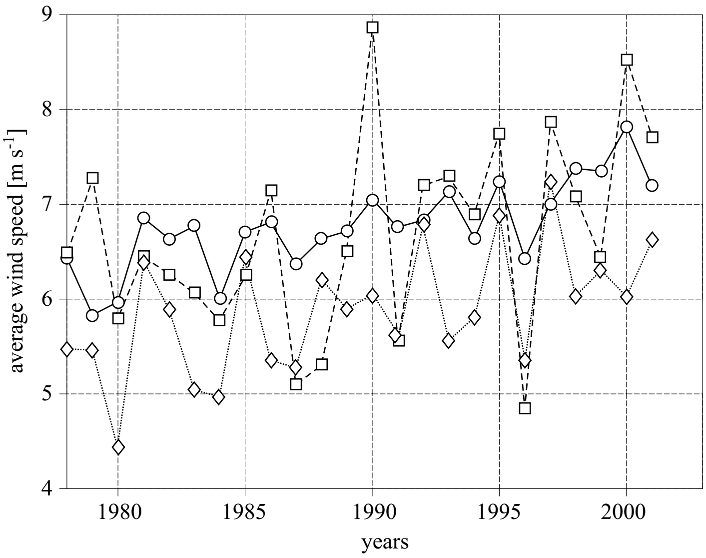


Fig. 9. The annual average wind speed (circles on solid line) and average wind speed at Utö in March (squares on dashed line) and April (diamonds on dotted line) 1978–2001

The WHM data cover only a small part of the years 1993 and 1994; however, the average properties of the wave field closely match those measured by the SimRad equipment. There are no WHM data from 1998, and there is a relatively long gap in the time series from July to December 2001.

The trends extracted from the WHM data are indistinct (the relevant correlation coefficient of a formal trend of the rapid decrease in the annual mean wave height is about 0.2) and possibly less reliable. While the average wave height measured by the WHM at the turn of the century is generally in line with the changes in the average wind speed, the rapidly falling trend in the annual average wave height in 1999–2003 does not match the relevant wind data (see Figs 8 and 9) and appears to be fictitious.

There is also some doubt whether the WHM data recorded in 1996–97 correctly represent the actual sea state. The wave conditions recorded in some months (June 1996 with a monthly mean of $H_{1/3}$ over 1 m, and particularly March–April 1997 with a monthly mean of $H_{1/3}$ of 2.6 and 2.8 m, respectively) are (partially unrealistically) severe (see Fig. 9). This becomes clear from a comparison of these data with wind data from Utö.

Although the annual mean wind speed does not necessarily exactly match the average wave height, it is intuitively clear that a larger wind speed generally causes greater wave activity. The wind speed in March–April 1997 (when the WHM data report extremely high wave activity) differs insignificantly from the relevant mean value over several consecutive years. Also, the measured annual mean wave height in 1996–97 is much higher than in other years. This feature does not correspond to Utö wind data either, which suggests that these years were relatively calm and that the wind speed in 1996 was exceptionally low compared to adjacent years (Fig. 9).

Wave conditions at Almagrundet exhibit a strong seasonal variability (Fig. 10). In this respect both the SimRad and the WHM data exhibit mostly similar behaviour. The annual variation in the monthly mean wave height is impressive, varying from about 0.5 m during the summer to 1.3–1.4 m in winter. The highest wave activity occurs from November to January. The WHM data suggest that another wave height maximum may

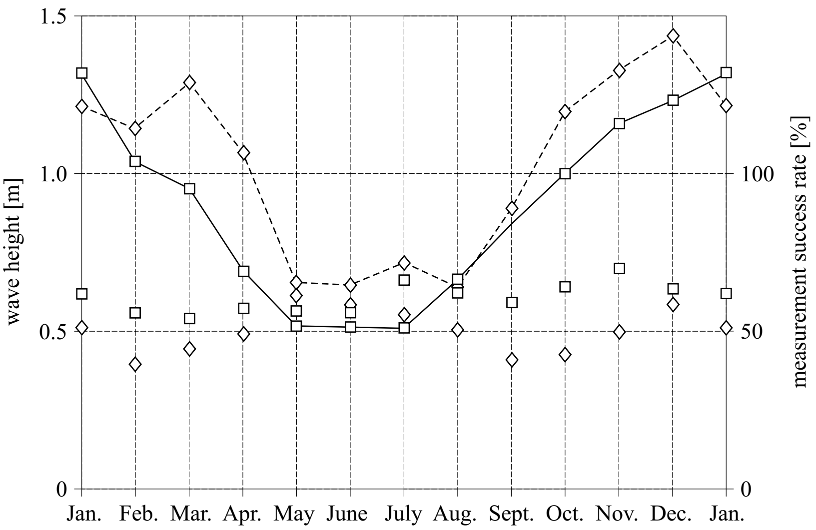


Fig. 10. The monthly mean wave height measured by the SimRad (squares on solid line) and the WHM (diamonds on dashed line) equipment. The measurement success rate (separated squares and diamonds) is the percentage of acceptable measurements within a particular month

occur in March. The above has shown that this feature may be questionable, although Fig. 9 shows that in some years March can be fairly windy.

The calmest months are in the late spring and summer months from May to July or August. Such an annual variation mostly matches the annual variation of the wind speed in the northern Baltic Proper (see Mietus 1998).

6. Discussion

From Kahma et al. (2003) and Soomere et al. (2006) it follows that since the beginning of measurements in the open part of the NBP in 1996, the significant wave height has exceeded 7 m only four times. This happened twice in December 1999, again twice in three weeks during the 2004–05 winter storms (once in December 2004 (see www.fimr.fi), and once on 9 January 2005 during windstorm Gudrun).

The above analysis has shown that the significant wave height probably exceeded this threshold on at least two occasions in the 1980s. The 1984 January storm was probably the most ferocious and long-lasting one until the 2005 January storm.

Since there is some difference in the measurement routine and in the principles of raw data analysis at Almagrundet compared to the directional waverider data, these time series are not directly comparable with each other. Yet this analysis suggests that, in general, neither the frequency nor the intensity of extreme wave storms has increased during the last thirty years. Extremely strong storms with significant wave heights close to or exceeding 7 m seem to occur roughly twice a decade. This is consistent with the observation that the number of active cyclones has not radically changed during recent decades.

However, the tendency towards an overall increase in wave activity in terms of the annual mean significant height can be identified from the analysed data. The rate of this increase is approximately the same as for the North Atlantic. It is important to emphasise that, given the specific conditions of the Baltic Sea and the Almagrundet measurement site, this trend may be either partially or wholly caused by other changes in the wind field. A theoretically possible but unlikely explanation is that the intensity of winds from the south and east has increased.

Since the wave conditions at Almagrundet are relatively strongly dependent on the wind direction, a part of the seasonal variation in the wave intensity at this site may reflect differences in the dominant wind directions in different seasons. In particular, a large portion of easterly winds occurs in the northern Baltic Proper during the late winter and early spring (Mietus 1998). This feature may be one of the reasons for the relatively high wave intensity at this site in February and March.

References

Bacon S., Carter D. J. T., 1991, *The wave climate changes in the North-Atlantic and North Sea*, Int. J. Climatol., 11, 545–558.

Blomgren S., Larsson M., Hanson H., 2001, *Numerical modelling of the wave climate in the southern Baltic Sea*, J. Coast. Res., 17 (2), 342–352.

Boukhanovsky A. V., Lavrenov I. V., Lopatoukhin L. J., Rozhkov V. A., Divinsky B. V., Kos'yan R. D., Ozhan E., Abdalla S., 1999, *Persistence wave statistics for Black and Baltic seas*, Proc. Int. MEDCOAST Conf. 'Wind and wave climate of the Mediterranean and the Black Sea', Antalya, Turkey, 199 –210.

Davidan I. N., Lopatoukhin L. I., Rozhkov V. A., 1978, *Wind sea as a probabilistic hydrodynamic process*, Gidrometeoizdat, Leningrad, 287 pp., (in Russian).

Davidan I. N., Lopatoukhin L. I., Rozhkov V. A., 1985, *Wind waves in the world oceans*, Gidrometeoizdat, Leningrad, 256 pp., (in Russian).

Gayer G., Günther H., Winkel N., 1995, *Wave climatology and extreme value analysis for the Baltic Sea area off the Warnemünde harbour entrance*, Dt. Hydrogr. Z., 47, 109–130.

Gulev S. K., Hasse L., 1999, *Changes of wind waves in the North Atlantic over the last 30 years*, Int. J. Climatol., 19 (10), 1091–1117.

IAHR working group on wave generation and analysis, 1989, *List of sea-state parameters*, J. Waterw. Port Coast. Ocean Eng., 115, 793–808.

Jönsson A., Broman B., Rahm L., 2002, *Variations in the Baltic Sea wave fields*, Ocean Eng., 30, 107–126.

Jönsson A., Danielsson A., Rahm L., 2005, *Bottom type distribution based on wave friction velocity in the Baltic Sea*, Cont. Shelf Res., 25 (3), 419–435.

Kahma K., 1981, *On two-peaked wave spectra*, Finn. Mar. Res., 248, 87–116.

Kahma K., Pettersson H., 1993, *Wave statistics from the Gulf of Finland*, Finn. Inst. Mar. Res. Internal Rep. No 1/1993, (in Finnish with English summary).

Kahma K., Pettersson H., 1994, *Wave growth in a narrow fetch geometry*, Global Atmos. Ocean Syst., 2, 253–263.

Kahma K., Pettersson H., Tuomi L., 2003, *Scatter diagram wave statistics from the northern Baltic Sea*, Finn. Inst. Mar. Res. Rep. Ser. No 49, 15–32.

Kahma K., Rantanen E., Saarinen J., 1983, *Wave data from the southern Bothnian Sea 1973–1975*, 1981, Finn. Inst. Mar. Res. Internal Rep. No 1/1983, (in Finnish with English summary).

Mårtensson N., Bergdahl L., 1987, *On the wave climate of the Southern Baltic*, Dept. Hydraulics, Chalmers Univ. Technol., Göteborg, Rep. Ser. A:15,

Mietus M., (co-ordinator), 1998, *The climate of the Baltic Sea Basin, Marine meteorology and related oceanographic activities*, World Meteorol. Org., Geneva, Rep. No 41.

Mietus M., von Storch H., 1997, *Reconstruction of the wave climate in the Proper Baltic Basin, April 1947–March 1988*, GKSS Rep. No 97/E/28, Geesthacht.

Orlenko L. R., (ed.), 1984, *Studies of the hydrometeorological regime of Tallinn Bay*, Gidrometeoizdat, Leningrad, (in Russian).

Paplińska B., 1999, *Wave analysis at Lubiatowo and in the Pomeranian Bay based on measurements from 1997/1998 – comparison with modelled data (WAM4 model)*, Oceanologia, 41 (2), 241–254.

Pettersson H., 1994, *Directional wave statistics from the southern Bothnian Sea 1992*, Finn. Inst. Mar. Res. Internal Rep. No 5/1994, (in Finnish with English summary).

Pettersson H., 2001, *Directional wave statistics from the Gulf of Finland 1990 –1994*, Finn. Inst. Mar. Res. Rep. Ser. No 44, 1–37, (in Finnish with English summary).

Pettersson H., 2004, *Wave growth in a narrow bay*, Ph. D. Thesis, Finn. Inst. Mar. Res. Contributions No 9.

Pettersson H., Boman H., 2002, *High waves and sea level during the November storm*, Annual report 2001, Finn. Inst. Mar. Res., Helsinki, p. 7.

Soomere T., 2003, *Anisotropy of wind and wave regimes in the Baltic Proper*, J. Sea Res., 49 (4), 305–316.

Soomere T., 2005, *Wind wave statistics in Tallinn Bay*, Boreal Environ. Res., 10 (2), 103–118.

Soomere T., Behrens A., Tuomi L., Nielsen J. W., 2006, *Unusual wave conditions in the northern Baltic Sea during windstorm Gudrun in January 2005*, Geophys. Res. Abstr., 8, paper 02851.

Soomere T., Keevallik S., 2001, *Anisotropy of moderate and strong winds in the Baltic Proper*, Proc. Estonian Acad. Sci. Eng., 7 (1), 35–49.

Suursaar Ü., Kullas K., Otsmann M., Saaremäe I., Kuik J., Merilain M., 2006, *Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters*, Boreal Environ. Res., 11 (2), 143 –159.

Svensson J., 1984, *Vågdata från svenska kustvatten 1983*, Projectresultat Rfn/LET 1984:26.

Vikebo F., Furevik T., Furnes G., Kvamsto N. G., Reistad M., 2003, *Wave height variations in the North Sea and on the Norwegian Continental Shelf 1881 –1999*, Cont. Shelf Res., 23 (3–4), 251–263.

WASA Group, 1995, The WASA project: *Changing storm and wave climate in the northeast Atlantic and adjacent seas?*, Proc. 4th Int. Workshop 'Wave Hindcasting and Forecasting, Banff, Canada, October 16–20, 31–44, [also: GKSS Rep. 96/E/61].