Extremes and Decadal Variations of the Northern Baltic Sea Wave Conditions

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Abstract Average wave conditions, their seasonal cycle and decadal variations, and extreme wave storms in the northern Baltic Sea are studied on the basis of long-term time series from Almagrundet (1978–2003) and Vilsandi (1954–2005), and wave statistics from the middle of the northern Baltic Proper. The typical wave periods are 3–4 s in coastal areas and 4–6 s on the open sea. The monthly mean wave height varies from about 0.4 (0.5) m in April–July to 0.8 (1.3–1.4) m in January at Vilsandi (Almagrundet). The annual mean wave height varied insignificantly in the 1960s–1970s, considerably increased in the 1980s, was at highest in the mid-1990s, and rapidly decreases in 1998–2005. Significant wave heights $H_S \geq 4$ m occur with a probability of about 1%. Extreme wave conditions with $H_S \geq 7$ m have been registered five times since 1978. The records overlook 2–3 such cases. The overall recorded maximum H_S is 7.8 m. The estimated maximum of H_S was 9.5 m in cyclone Gudrun in January 2005.

1 Introduction

The complexity of physics and dynamics of the Baltic Sea extend far beyond the typical features of many other water bodies of comparable size (e.g. Alenius et al. 1998). The combination of a relatively small size and vulnerability of its ecosystem makes this region extremely susceptible with respect to climate changes and shifts. Numerous changes of the forcing conditions and of the reaction of the water masses of the Baltic Sea have been reported during the latter decade. The apparently increasing storminess in the Baltic Sea has already caused extensive erosion of depositional coasts (Orviku et al. 2003), although the changes in the wave climate have been found marginal, at least, until the mid-1990s (WASA Group 1995; Mietus and Storch 1997).

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Very rough seas measured twice in December 1999 reinforced the discussion whether the wave conditions in the Baltic Sea have become rougher compared with the situation a few decades ago. The exceptional storm Erwin/Gudrun of January 2005 highlighted inadequate awareness of extreme wave properties (Soomere et al. 2008) and of the height and spatial extent of extreme water levels (Suursaar et al. 2006).

Recognition of the wave climate changes, in particular, changes of extremes, presumes a thorough knowledge of the typical and extreme wave conditions The global wave data set KNMI/ERA-40 Wave Atlas (09.1957–08.2002, Sterl and Caires 2005) allows the production of reliable wave climatology for open ocean conditions, based on 6-hourly means of wave properties over an average of $1.5^\circ \times 1.5^\circ$ areas. This resolution is too sparse for the Baltic Sea conditions.

The wave properties in the Baltic Sea can be modelled with the use of local models, because the waves from the rest of the World Ocean practically do not affect this water body. The pattern of dominant winds (Mietus 1998; Soomere and Keevallik 2001) and the geometry of the Baltic Sea suggest that the highest and longest waves occur either at the entrance of the Gulf of Finland, off the coasts of Saaremaa, Hiiumaa, and Latvia, or along the Polish coasts. Wave data from the northern parts of the Baltic Sea Proper thus adequately represent both the average and the roughest wave situations in the region.

Wave statistics for the Baltic Proper has been recently estimated with the use of the second-generation spectral wave model HYPAS and wind data from 1999 to 2000 (Jönsson et al. 2002, 2005; Danielsson et al. 2007). The overall picture of wave activity follows the above-described wind pattern. Several numerical wave studies are performed for the southern part of the Baltic Sea (e.g. Gayer et al. 1995; Paplińska 1999; Blomgren et al. 2001). Valuable wave data and statistics are presented in sources published in the former USSR (Rzheplinsky 1965; Rzheplinsky and Brekhovskikh 1967; Davidan et al. 1978, 1985; Lopatukhin et al. 2006a, b).

Yet the information about long-term changes of wave properties is fragmentary in the Baltic Sea. This water body is characterised by extremely complex geometry, highly varying wind fields, extremely rough wave conditions at times, extensive archipelago areas with specific wave propagation properties, and the ice cover during a large part of each year. The quality of wind information only allows reasonable reproduction of wave patterns since 1990s. Although third generation wave models (e.g. Komen et al. 1994) have been implemented for the northern Baltic Sea at the turn of the millennium (e.g. Tuomi et al. 1999; Soomere 2001), wave statistics based on such models is available only for limited areas (Soomere 2003, 2005).

An adequate long-term simulation of the Baltic Sea wave fields is still missing. Also, no comprehensive description of the wave climate or statistical estimates of extreme wave conditions exists in the whole Baltic Proper.

The central goal of this study is to present a systematic description of the basic properties of average and extreme wave conditions and to depict their durable changes in the northern Baltic Proper on the basis of available long-term wave measurements and numerical simulations of a specific event. The wave patterns in the

Gulf of Finland (an elongated basin with a length of about 400 km and a maximum width of about 135 km) are frequently connected with those in the Proper, and are addressed to some extent as well.

The analysis is mostly based on instrumental measurements in 1978–2003 at Almagrundet (located near the western coast of the northern Baltic Proper) and on visual observations from the island of Vilsandi in 1954–2003 (the eastern coast of the Baltic Proper). To a limited extent, data from waveriders in the middle of the northern Baltic Proper and from Bogskär are used. The results predominantly represent Type A statistics in terms of the classification of Kahma et al. (2003): almost no corrections have been made to compensate for missing values, for the uneven distribution of data (except for the use of daily mean wave heights for certain parameters), or for ice cover. Modelled data are used in the estimates of extreme waves in windstorm Gudrun in January 2005.

2 Wave Climate in the Northern Baltic Proper

2.1 Data from Almagrundet, Bogskär and from the Open Sea

Contemporary wave measurements were launched in the northern Baltic Sea in the framework of wave power studies at the end of the 1970s near the lighthouse of Almagrundet and south of Öland. A waverider buoy was simultaneously deployed near Hoburg, south of Gotland. The measurements were mostly performed during a few years (Mårtensson and Bergdahl 1987), but went on longer at Almagrundet.

The data from Almagrundet (1978–2003, 59°09′N, 19°08′E, Fig. 1, Broman et al. 2006) form the longest instrumentally measured wave time series in this region. The above-discussed anisotropy of the Baltic Sea wave fields has caused some discussion about whether the data correctly represent the open-sea wave conditions (Kahma et al. 2003). Almagrundet is a 14 m deep shoaling area about 10 nautical miles south-east of Sandhamn in the Stockholm archipelago. It is sheltered from a part of dominating winds. The fetch length for winds from the south-west, west, and north-west is quite limited. Yet the data constitute one of the most valuable data sets for the Baltic Sea.

An upward-looking echo-sounder from Simrad was placed at a depth of about 30 m in 1978 (Mårtensson and Bergdahl 1987) and was active until mid-September 1995 at Almagrundet. An analogous device from WHM was installed in a neighbouring location at a depth of 29 m in 1992 and produced usable data in 1993–2003 (Broman et al. 2006). The position of the water surface was sampled during 640 s each hour. Wave components with periods of less than 1.5 s as well as the data probably reflecting wave interference and breaking waves and possibly very steep waves were discarded (Mårtensson and Bergdahl 1987). Single waves were identified on the basis of the classical zero-downcrossing method (IAHR 1989). An estimate of the significant wave height $H_{1/3}$ (the average height of 1/3 of the highest waves) was

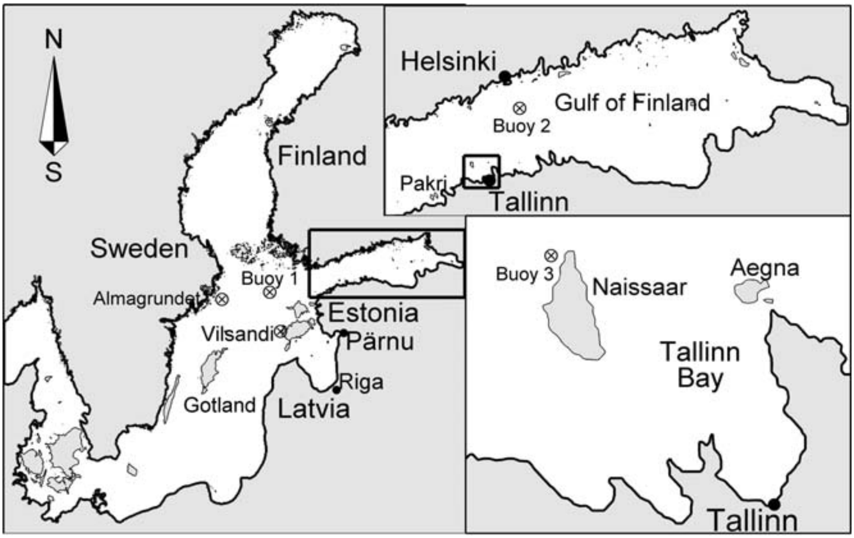

Fig. 1 Wave measurement sites, marked by *crossed circle*, at Almagrundet, at the Island of Vilsandi, in the northern Baltic Proper (buoy 1), near Helsinki (buoy 2) and at the Island of Naissaar (buoy 3)

found from the 10th highest wave H_{10} in a record of N waves under the assumption that wave heights are Rayleigh distributed:

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

The set of 95,458 measurements in 1978–1995 reliably describes the wave properties (Broman et al. 2006). Later 46,671 recordings in 1993–2003 have certain quality problems. The overall behaviour of the wave height apparently follows the sea state; yet the data contain a number of modest but still evidently unrealistic peaks. As the values of wave period are also unreliable, Broman et al. (2006) recommend considering the data as merely indicative.

A non-directional waverider was operated in 1983–1986 near Bogskär at 59°28.0′N, 20°21.0′E (Kahma et al. 2003). The wave properties were measured hourly. The total measuring time is 14,630 h, or about 2 years of uninterrupted measurements. The measuring times, however, are concentrated in the autumn season and thus well represent the wave climate during relatively windy months.

A directional waverider was deployed in the northern Baltic Proper at a depth of about 100 m (buoy 1 in Fig. 1, 59°15′N, 21°00′E) in September 1996 and operated since then during the ice-free seasons (Kahma et al. 2003). This device as well as contemporary spectral wave models estimate the significant wave height as $H_S = 4\sqrt{m_0} \approx H_{1/3}$, where m_0 is the zero-order moment of the wave spectrum (the total variance of the water surface displacement, e.g. Komen et al. 1994). These data are the most representative of the Baltic Sea wave fields; however, to date, this time series is not long enough for determining the climatological values of wave properties (Guide 2001).

Directional wave measurements in the Gulf of Finland in 1990–1991, 1994, and from November 2001 (59°57.9′N, 25°14.1′E, water depth about 60 m, buoy 2 in Fig. 1) during the ice-free seasons have considerably increased the awareness of wave conditions in semi-enclosed sub-basins of the Baltic Sea (Kahma and Pettersson 1993; Pettersson 2001; Kahma et al. 2003). Hardly any instrumental wave data are available from the coastal areas of Estonia and Latvia, except for sporadic measurements made with pressure-based sensors (Soomere 2005).

2.2 Visual Observations from the Island of Vilsandi

A reasonable source of the open sea wave information form visual observations from the ships (Hogben et al. 1986). Wave climate changes estimated from data observed from merchant ships are consistent with those shown by the instrumental records (Gulev and Hasse 1998, 1999). Visual observations from the coast are less frequently used for wave climate studies. Although such observations frequently represent only wave properties in the immediate vicinity of the observation point (Orlenko et al. 1984), have a poor temporal resolution, may give a distorted impression of extreme wave conditions, have many gaps caused by inappropriate weather conditions or by the presence of ice, etc., the data are one of the few sources for detecting the long-term changes of wave climate.

The coastal site adequately reflecting the open sea wave conditions (except for easterly winds) is located at the Island of Vilsandi (58°22′59″N, 21°48′55″E, Fig. 1). Wave observations were performed there starting from 1954 up to three times a day. The interval between subsequent observations is often much longer than the typical saturation time of rough seas in the northern Baltic Proper (about 8 h, Soomere 2001) or the duration of wave storms (that seldom exceeds 10 h, Broman et al. 2006; Lopatukhin et al. 2006b). The data, however, well represent the general features of the Baltic Sea wave fields: relatively low overall wave activity, short wave periods, and substantial seasonal variation of wave conditions (Soomere and Zaitseva 2007).

The observer noted the five highest waves during a 5-min time interval and filed the highest single wave $H_{\max}$ and the mean height H of these waves at Vilsandi. Given the typical wave periods in the coastal zone 3–4 s (Broman et al. 2006), the height H is approximately equal to the average height of 2.5–3% of the highest waves. As the observers' estimates well represent the significant wave height (Gulev and Hasse 1998, 1999), we shall interpret H as an estimate of the significant wave height and shall use it whenever given in the data set. Only when this measure is missing, $H_{\max}$ is used instead. As the difference between H and $H_{\max}$ is about 6% in average (Soomere and Zaitseva 2007), doing so apparently has a fairly minor influence on climatological values of wave heights.

The wave period was found as an arithmetic mean from three consecutive observations of passing time of 10 waves each time. Since the visually observed wave periods are only a few tenths of seconds shorter than the peak periods (Gulev and Hasse 1999), the results are interpreted as estimates of the peak period. All obviously erroneous, ambiguous, or inconsistent entries in the observation diaries were omitted in the analysis of Soomere and Zaitseva (2007). At least one sensible observation of the wave height has been made on 15,038 days (coverage 79%). Most of the gaps occur from January to March apparently owing to the presence of sea ice.

2.3 Wave Climate

2.3.1 Wave Statistics in the Northern Baltic Sea

The wave climate of the northern Baltic Sea is relatively mild (Table 1). The overall average of the significant wave height at the open sea may slightly exceed the one estimated from Almagrundet data, but apparently it is close to 1 m.

The overall average wave height calculated from the entire Vilsandi data set is much smaller. The excess proportion of calms at Vilsandi (>30%, Soomere and Zaitseva 2007) is evidently due to the absence of observable waves in many cases of easterly winds. Removing a fraction of calms from this set is therefore roughly equivalent to ignoring data inadequately reflecting the open sea wave fields in such wind conditions. If the number of calms is reduced to 6% from the total number of recordings (the level typical for the northern Baltic Proper, Fig. 2), the average wave height at Vilsandi is 0.74 m.

The wave heights at Almagrundet in 1993–2003 (WHM data) may be slightly overestimated because of certain small, but evidently unrealistic peaks. The analysis of the Vilsandi data relies on the daily average wave height

The probability distributions of the occurrence of different wave heights at Almagrundet, Bogskär, and on the open sea (Fig. 2) resemble the Rayleigh distribution. This distribution at Vilsandi resembles analogous distributions for wave heights in semi-sheltered bays of the Baltic Sea (Soomere 2005).

Table 1 Basic properties of wave fields at Almagrundet and Vilsandi

Data set	Overall average wave height	Median wave height	Most frequent	
			wave height	wave period
Almagrundet 1978–95 (1993–2003)	0.876 (1.04)	0.7 (0.73)	0.25–0.5	3 (–)
Vilsandi 1954–2005 (6% calms kept)	0.575 (0.74)	0.3 (0.5)	<0.25 (0.25–0.5)	3 (3)
Bogskär 1982–1986	–	–	0.5–0.75	5
Northern Baltic Proper	–	–	0.25–0.5	5

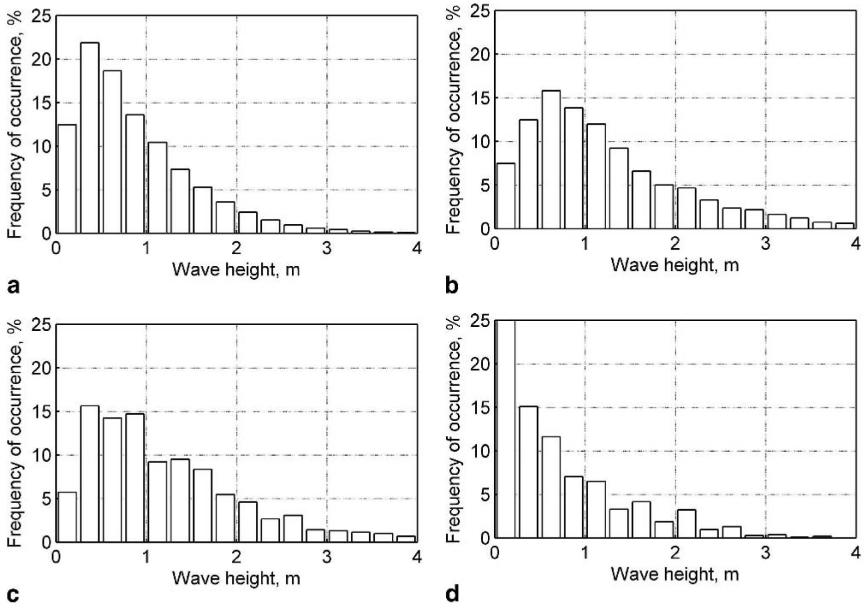

Fig. 2 Frequency of occurrence of wave heights at (**a**) Almagrundet 1978–1995, (**b**) Bogskär 1982–1986, (**c**) at buoy 1 in the northern Baltic Proper, (**d**) at Vilsandi

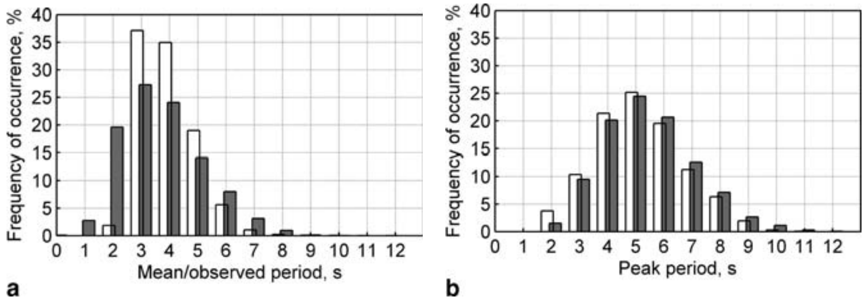

Fig. 3 Frequency of occurrence of wave periods: (**a**) Almagrundet 1978–1995 (*white bars*) and Vilsandi 1954–2005 (*filled bars*), (**b**) Bogskär 1982–1986 (*white bars*) and buoy 1 in the northern Baltic Proper 1996–2000 (*filled bars*)

Most frequently waves with periods of 4–6 s dominate in the middle of the Baltic Proper whereas in the coastal regions waves with periods of 3–4 s predominate (Fig. 3). Wave periods about 5–6 s also occur with an appreciable frequency in the coastal areas. Periods up to 7 s are still common on the open sea. This difference in periods apparently comes from a relatively large number of short-fetched wave conditions at sheltered measurement sites.

The joint distributions of wave heights and periods (Fig. 4) suggest that the proportion of relatively steep seas is quite large in the Baltic Sea. Periods of 2–3 s usually correspond to wave heights well below 1 m whereas waves with periods of 4–5 s

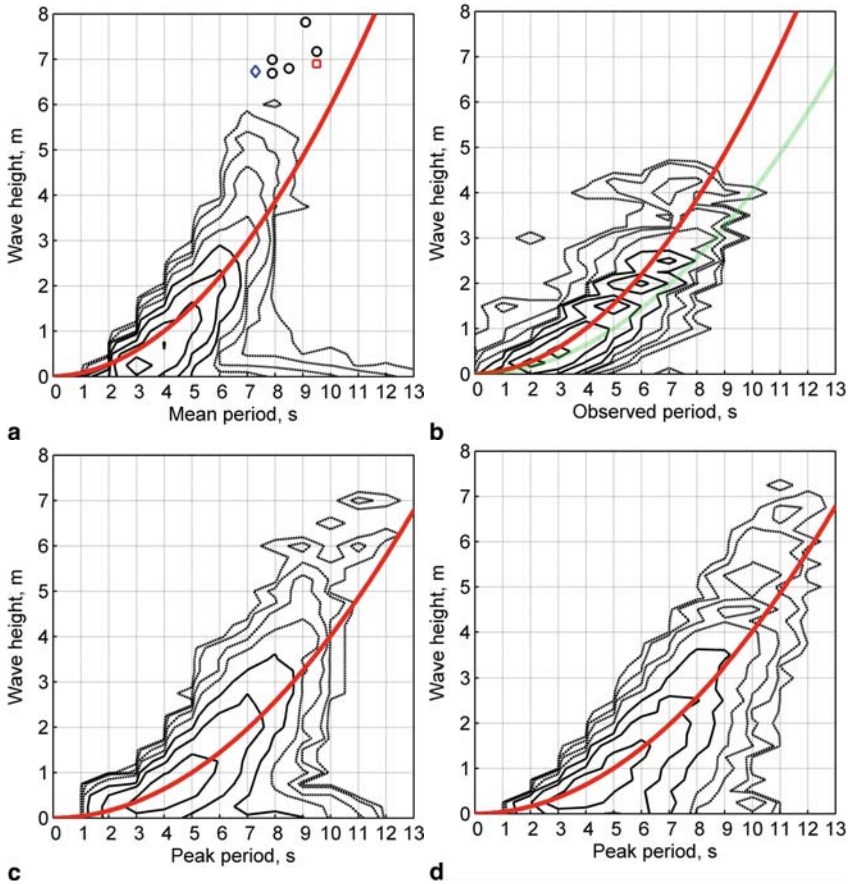

Fig. 4 Scatter diagram of wave heights and periods: (**a**) Almagrundet 1978–1995, (**b**) Vilsandi in 1954–1994, (**c**) Bogskär 1982–1986, (**d**) buoy 1 in the northern Baltic Proper. The wave height step is 0.25 m and the period step is 1 s. The range of periods is shown on the horizontal axis: 2 s stands for $1.5 \leq T_p < 2.5$ s, 3 s stands for $2.5 \leq T_p < 3.5$ s, etc. Isolines for the probability of occurrence of 0.0033%, 0.01%, 0.033%, 0.1% (*dashed lines*), 0.33%, 1%, 3.3%, and 10% (*solid lines*) are plotted. Wave conditions with $H_{1/3} > 6.5$ m at Almagrundet are shown as follows: *circles* – the January 1984 storm, *diamond* – a storm in January 1988, *square* – a storm in August 1989. The *bold line* indicates saturated wave conditions with a Pierson-Moskovitz spectrum. The *bold grey line* in panel (**b**) indicates saturated wave situation in terms of the peak period

have a typical height of about 1 m. Periods 6–7 s usually correspond to wave heights of about 1.5–2 m. In coastal areas, dominating periods are 7–8 s only when wave heights are about 3 m or higher. Even longer waves are infrequent. Mean periods over 8 s (peak periods ≥ 10 s) dominate either in very rough seas (wave heights over 4 m) or in remote low swell conditions when the wave heights are well below 1 m. For example, at Almagrundet the mean period never exceeded 9.5 s in very rough seas and was about 10 s in one case of rough seas with $H_{1/3} \sim 4$ m. Even in the final

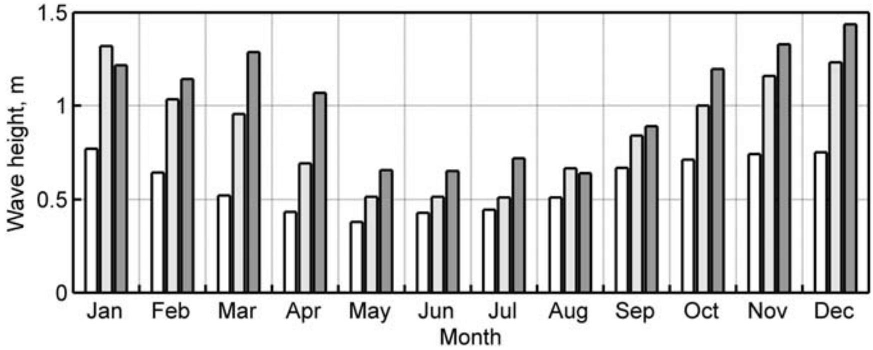

Fig. 5 Annual variation of the monthly mean wave height at Vilsandi 1954–2005 (*white bars*, based on the daily mean wave height) and at Almagrundet 1978–1995 (*light grey bars*) and 1993–2002 (*dark grey bars*)

stage of the January 1984 storm when $H_{1/3} \sim 7$ m, the mean period was below 10 s. At the location of buoy 1, the peak period of about 12 s has been registered about twice a year and at Bogskär roughly once in two years.

The annual variation in the monthly mean wave height matches the similar variation of the wind speed (Mietus 1998). It is impressive at Almagrundet: from about 0.5 m during summer to 1.3–1.4 m in winter (Fig. 5). It is somewhat less pronounced at Vilsandi: from about 0.4 m during summer to about 0.8 m in winter.

The highest monthly mean wave height occurs from November to January at Almagrundet. Another wave height maximum may occur at Almagrundet in March (Broman et al. 2006). It is apparently connected with easterly winds during late winter and early spring (Mietus 1998), and the influence of which is not detectable at the sheltered observation site of Vilsandi. The highest wave activity at Vilsandi generally occurs in January, but during October to December a comparable wave activity is observed. The calmest period is the late spring and summer months from May to July–August whereas a well-defined minimum in May is visible in Vilsandi data.

2.3.2 Extreme Conditions

Estimates of extreme wave conditions with the use of the WAM model forced by homogeneous wind patterns suggest that the significant wave height generally does not exceed 8–8.5 m in the northern Baltic Proper (Soomere 2001). This estimate is confirmed by Lopatukhin et al. (2006a).

Seas in which $H_S > 7$ m are extremely rough in the Baltic Sea basin. This threshold was not reached at Bogskär in 1982–1986. Waves of this height cannot be observed from Vilsandi, because the depth of the observation area is about 4 m. The most ferocious storm (the only one during which $H_{1/3} \geq 7$ m was registered at the site) occurred at Almagrundet on 13–14 January 1984 when $H_{1/3}$ reached

7.82 m and the highest single wave was 12.75 m high[1] (Broman et al. 2006). This is, formally, the largest significant wave height ever recorded in the northern Baltic Sea[2]. The wave periods remained fairly modest ($T_m = 9.1$ s, $T_p = 10.7$ s).

The wave height reached $H_{1/3} = 6.9$ m in a relatively short but violent storm in August 1989 and $H_{1/3} = 6.73$ m in another severe storm on 30 January 1988 at Almagrundet. The significant wave height on the open sea apparently exceeded 7 m during these events. No reliable data are available for a severe storm in January 1993.

The significant wave height exceeding 7 m has been recorded only four times by buoy 1: twice in December 1999 (whereas $H_{1/3}$ was about 6 m at Almagrundet, Kahma et al. 2003), on 22 December 2004 [when the roughest wave conditions $H_S = 7.7$ m, and the highest single wave (14 m) were recorded for this site, see http://www.fimr.fi] and on 9 January 2005 during windstorm Gudrun (Soomere et al. 2008). The peak periods during these events slightly exceeded 12 s.

Rough seas with the (observed or measured) wave heights over 4 m occurred with a probability of 0.2% (about once a year) at Vilsandi, of 0.42% in 1978–1995 at Almagrundet, of 1% at Bogskär, and of 1.4% at buoy 1. Such seas usually occur several times a year, each time during a few hours.

2.3.3 Gulf of Finland

The average and, in particular, the maximum wave heights in the Gulf of Finland are much smaller than in the Baltic Proper. The 'memory' of wave fields is relatively short, and the changes in the wind field are fast reflected in the wave pattern. As a consequence, the wave fields in smaller sub-basins (such as Tallinn Bay or Narva Bay) mimic the changes of the open-sea winds (Soomere 2005; Laanearu et al. 2007).

On the basis of data from 1990–1991 and 1994, the maximum H_S occurring once in 100 years in the Gulf of Finland was estimated to be 3.8 m and the corresponding single wave height 7.1 m. Wave conditions with $H_S > 4$ m occur extremely seldom (Alenius et al. 1998; Pettersson 2001). The peak periods in rough seas (with $H_S \sim 4$ m) are 8–9 s (Kahma and Pettersson 1993).

Recent data show that considerably rougher seas may occur in this area. In November 2001, seas with $H_S = 5.2$ m and $T_P \approx 11$ s occurred (Pettersson and Boman 2002). Wave systems with $T_P \geq 10$ s, however, usually correspond to penetration of long-period swell of moderate height into the gulf (cf. Broman et al.

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[1] The significant wave height, calculated directly from the wave spectrum, was $H_S = 7.28$ m.

[2] The Almagrundet data set contains several contradicting extreme wave data. A severe storm that affected nearly the whole Baltic Proper caused $H_{1/3} = 7.83$ m, formally the all-highest of the data set, in March 1997. Since H_S estimated from the wave spectrum was 5.7 m and the highest single wave reached 10.24 m, this value of $H_{1/3}$ evidently overestimates the wave conditions. An extremely high single wave (12.79 m) was recorded on 25 December 1996 when $H_{1/3} = 6.37$ m. Still the significant wave height, estimated from the wave spectrum, was only 3.8 m (Broman et al. 2006).

2006). Only a few observations reveal such long periods: $T_P \approx 11$ s occurred only three times in 1990–1994 and during a short time in another very strong storm in November 2001 (Pettersson 2001).

The average wave directions are often concentrated along the gulf axis (Pettersson 2001), although the wind directions are more evenly spread (Soomere and Keevallik 2003). This phenomenon is attached to the slanting fetch conditions in which the wind direction is oblique to the coastline (The SWAMP Group 1985, Chap. 8). Shorter waves are usually aligned with the wind, while somewhat longer and higher waves (that often dominate the wave field) propagate along the gulf axis (Holthuijsen 1983; Kahma and Pettersson 1994; Pettersson 2004).

3 Interannual and Long-Term Variations

The most intriguing question is whether any long-term changes in the wave activity can be identified in the Baltic Proper. The total duration of the measurements is about 25 years at Almagrundet and 52 years at Vilsandi. The series thus are long enough to extract climatological trends (Guide 2001).

The overall course of wave activity (Fig. 6) reveals a quasiperiodic variation. The interval between subsequent periods of high or low wave activity is about 25 years. The sea was comparatively calm at the end of the 1950s, became slightly rougher in 1965–1975, and calmer again at the end of the 1970s. A rapid increase in the annual mean wave height occurred from the mid-1980s until the mid-1990s. The increase was well over 1% per annum depending on the particular choice of the time interval and the site (Almagrundet 1979–1992: 1.3%; 1979–1995: 1.8%; Vilsandi 1979–1995 as high as 2.8% per annum). This trend follows the analogous trends for the southern Baltic Sea. Its magnitude is comparable with the one reported for the North Atlantic (Bacon and Carter 1991; Kushnir et al. 1997), but it is much faster

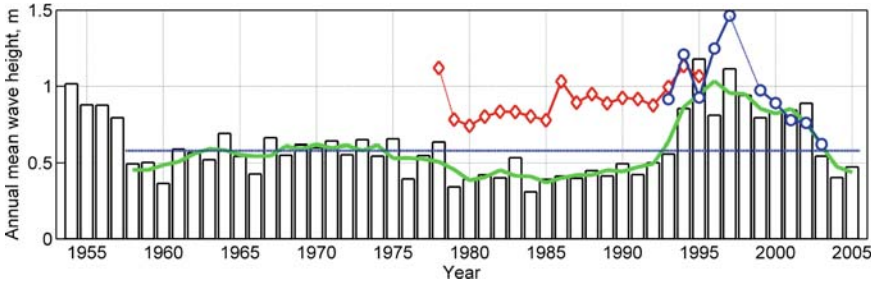

Fig. 6 The annual mean wave height at Vilsandi 1954–2005 (*bars, grey line*: 3-year moving average since 1958) and at Almagrundet 1978–1995 (*diamonds*) and 1993–2003 (*circles*). The *horizontal line* indicates the overall mean wave height at Vilsandi in 1958–2005. Notice that Almagrundet data from 1978 reflect only windy months November and December (Broman et al. 2006) and that the wave heights in 1954–1957 probably are overestimated at Vilsandi (Soomere and Zaitseva 2007). Data from Almagrundet for 1998 are missing

than in the North Sea (where it was <1% per annum, Gulev and Hasse 1999; Vikebo et al. 2003). The overall increase of wave heights is consistent with the increase of wind speed over the northern Baltic Sea (Broman et al. 2006) that is frequently associated with the increasing storminess since the middle of the twentieth century (Alexandersson et al. 1998).

This trend only existed during about 1.5 decades and was replaced by a drastic decrease of the mean wave height since 1997. The relevant data from Almagrundet were even estimated as doubtful by Broman et al. (2006), because the annual mean wind speed continued to increase and intensification of beach processes was reported along the downwind side of the coasts (Orviku et al. 2003). Although the 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 match of the long-term variation of wave properties at Almagrundet and Vilsandi suggests that both data sets adequately reflect the changing wave situation.

The drastic changes of the mean wave height on the background of the gradual increase of the mean wind speed (Broman et al. 2006) suggest that the local wave generation conditions have substantially changed within relatively short time intervals. In particular, the overall wave activity was exceptionally high at Almagrundet in 1996–1997, but the wind data from Utö (a small island in the northern Baltic Proper that well represents the open-sea wind conditions, Soomere 2003) suggest that these years were relatively calm.

4 Extremes During Windstorm Gudrun

4.1 The Storm and Waves

The above estimates for extreme wave conditions turned out to be inadequate when windstorm Gudrun, an extratropical cyclone, also known as Erwin in Ireland, the United Kingdom, and Central Europe, attacked northern Europe on 7–9 January 2005 (Carpenter 2005). It reached the power of a hurricane, according to the Saffir-Simpson hurricane scale (Simpson and Riehl 1981), in the North Sea region. In the Baltic Sea, it remained slightly below the hurricane level; yet it was one of the strongest storms in Denmark, Sweden, Latvia, and Estonia for at least 40 years. It caused widespread property damage, exceptionally high coastal floods along the Western Estonian coast and in the Gulf of Finland, and loss of 18 lives (Carpenter 2005; Suursaar et al. 2006; Bengtsson and Nilsson 2007). Substantial beach destruction occurred on exposed coasts (Orviku 2006).

The coastal wind data suffered from failures of meteorological equipment during Gudrun (Suursaar et al. 2006). Forecast winds from the German Weather Forecast Service (DWD, Deutscher Wetterdienst), the Danish Meteorological Institute (DMI), and the Finnish Institute of Marine Research (FIMR) suggest that the maximum wind speed on the open sea (Fig. 7) was 28–29 m s^{-1}. Forecasts released on 6–7 January predicted the windstorm maximum to hit the entrance of the Gulf of

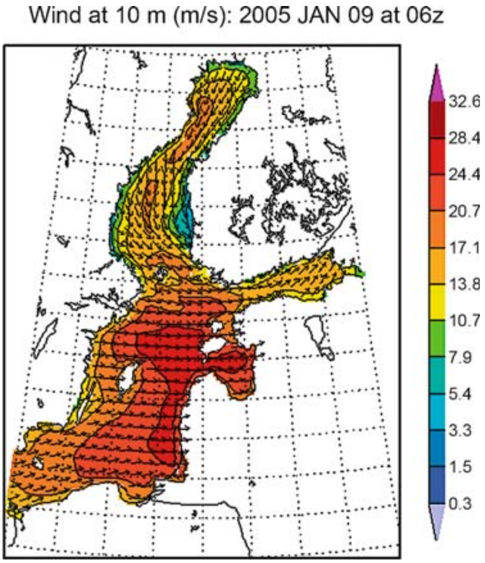

Fig. 7 Modelled wind speed (m/s) and direction (arrows) 10 m above water surface at 06:00 GMT on 9 January in the DMI 54-h forecast valid at 00:00 GMT on 9 January. Courtesy of the Danish Meteorological Institute

Finland. The significant wave height was forecast to exceed 10 m at buoy 1, to reach 11–12 m at the latitudes of the Gulf of Finland, and to be >6 m in the central part of this gulf (Soomere et al. 2008). Such wave conditions were considerably rougher than during any other storm in the northern Baltic Sea in the history of contemporary shipping (K. Kahma, personal communication on 8 January 2005). The area with the largest wind speeds crossed the Baltic Sea somewhat more southwards than originally forecast (Soomere et al. 2008) and the wave conditions were not so rough.

Buoy 1 adequately reflects extreme wave conditions in the case of SW winds, but the Gudrun's strongest winds were from W-WSW and occurred between Gotland and Saaremaa. The wave sensors therefore were located much northwards from the maximum of the wave storm. Even with these non-ideal conditions for wave generation and detection of the roughest seas, the significant wave height reached $H_S = 7.16$ m at 03:00 and 07:00 GMT on 9 January and was close to 7 m during about 12 h. The peak period T_P exceeded 10 s for nearly 24 h and was about 11–12 s at the wavestorm maximum.

Very long (T_p up to 12 s) and high ($H_S > 4$ m) waves also occurred in the Gulf of Finland during Gudrun. The significant wave height was close to 4 m in the early morning of 9 January and exceeded 3 m during the rest of this day at buoy 2. The peak periods were over 10 s during almost the whole day and reached 11–12 s at noon. The wave height was about 4 m in the morning of 9 January at the location of buoy 3 (a pressure sensor mounted north-westwards from the Island of Naissaar in 14 m deep water at $59°37.1'$N, $24°29.1'$E, see Fig. 1), and reached 4.5 m, the second highest instrumentally registered wave height in the central part of the gulf, at 09:00 GMT. The peak periods were $\sim$12 s during about 10 h (Soomere et al. 2008).

The occurrence of long and high waves in the interior of the Gulf of Finland is an important feature of this storm. The maximum wind speed in the northernmost part of the Baltic Proper and at the entrance of the gulf apparently was about 20–24 m s^{-1} (Fig. 7) and well below 20 m s^{-1} during a large part of the storm in the gulf (see also coastal data in Suursaar et al. 2006). Storms with a wind speed of about 20 m s^{-1} may excite peak periods about 12 s only if the fetch length is $\geq$600 km and the wind duration $\geq$18 h (Rosenthal 1986). Although growth curves of Kahma and Calkoen (1992) suggest that somewhat shorter duration ($\sim$15 h) and fetch ($\sim$350 km) are sufficient for generation of such seas, it is still probable that some other factors eventually contributed to the occurrence of the observed wave system in the Gulf of Finland. For example, topographic refraction caused by the coastal slopes of the entrance of the gulf may gradually redirect a part of waves propagating from the southern parts of the Baltic Proper.

4.2 Modelled Wave Fields

The operational centres of DWD, DMI, and FIMR run the wave model WAM cycle 4 (Komen et al. 1994) on a regular rectangular grid in shallow water mode without data assimilation. The models use different sources of hourly to three-hourly forecast winds at the standard height of 10 m above the surface level from different atmospheric models. The land-sea masks, bathymetry, computational grid, spatial and temporal resolution, and spectral range of the wave models are different as well (Soomere et al. 2004, 2008). The mesh size varies from $1/10°$ along latitudes and $1/6°$ along longitudes (the DWD model) down to $0.08° \times 0.08°$ (the FIMR model). The DWD and FIMR models use 24 equally spaced wave propagation directions whereas the DMI model uses 12 directions. The DWD and DMI models employ 25 frequency bands from 0.04177 in 10% steps. The FIMR model uses an extended range of 35 bands up to 1.073 Hz. The models have demonstrated reasonable performance in both typical and extreme wave conditions. For example, the mean relative error of the forecast of the maximum wave height in the five strongest storms is about 15% for 13 buoys operated by the DMI.

The models well reproduced the course of wave properties during windstorm Gudrun. The overall maximum of H_S at buoy 1 was overestimated by about 6% by the FIMR model and by 12–20% by the models of the DWD and the DMI (Table 1, Soomere et al. 2008). The wave models mostly followed the measured sea state (somewhat overpredicted the wave heights and underpredicted the wave periods) also in the Gulf of Finland.

4.3 Maximum of the Wave Storm

The overall maximum H_S during this storm is estimated by Soomere et al. (2008) by means of correcting the overall maximum of the modelled H_S with the use of

Table 2 Relative errors of operational wave models and the estimated overall maximum of the significant wave height in the Baltic Sea during windstorm Gudrun

Model	Overall maximum at buoy 1	Overprediction (m)	Relative error (%)	Modelled overall maximum of H_S (m)	Estimated overall maximum of H_S (m)
FIMR	7.6	0.44	5.8	10.2	9.6
DMI	8.96	1.80	20	11.7	9.4
DWD	8.17	1.01	12.4	10.95	9.59

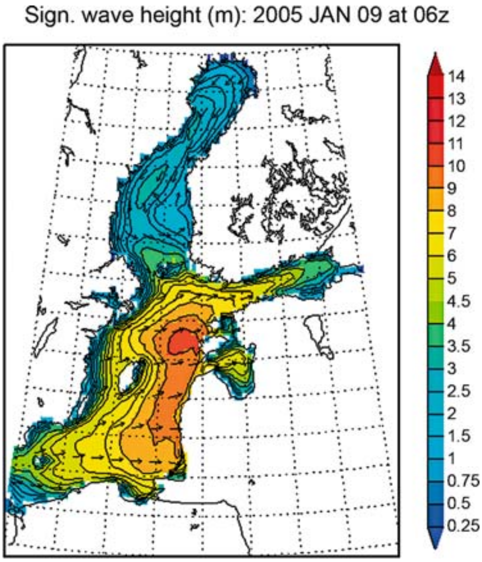

Fig. 8 Modelled significant wave heights (m) and wave propagation directions (*arrows*) at 06:00 GMT on 9 January in the DMI 54-h forecast valid at 00:00 GMT on 9 January. Courtesy of the Danish Meteorological Institute

the relative errors of the models calculated from observed data (Table 2). Doing so presumes that the wave models adequately represent the spatial patterns of wave properties and that the relative errors of the models are roughly the same over the entire area of intense waves. Since a large part of properties of the wave fields during Gudrun were located within the 'corridors' formed by outputs of the three models, a reasonable estimate of this maximum eventually lies between the values defined by these models.

The overall maximum $H_S \approx 9.5\,\text{m}$ during windstorm Gudrun evidently occurred about 200 km south-eastwards from buoy 1, off the coast of Saaremaa (about 57°N, 20.4°E, Fig. 8). Such wave conditions are much rougher than those expected to happen once in a century (Lopatukhin et al. 2006a). Waves were also remarkably long: peak periods up to 13 s were forecast (and eventually occurred) in the eastern part of the sea (Soomere et al. 2008).

The described procedure can be applied to the Gulf of Finland only based on results from buoy 2, because buoy 3 was located at a considerably smaller depth at a distance of >10 km from the closest model point. The significant wave height evidently reached 5 m in the gulf but most probably did not exceed the historical maximum $H_S = 5.2$ m.

5 Discussion

The most surprising outcome from the above analysis is that no overall increase of the average wave height has occurred in the northern Baltic Proper within the second half of the twentieth century. The annual mean wave height considerably increased in the 1980s and was exceptionally high in the mid-1990s, but quickly decreased starting from about 1997.

The long-term behaviour of the mean wave height matches neither the gradual increase of the mean wind speed nor the behaviour of the annual amplitude of the monthly mean sea level at the eastern coast of the Baltic Sea. This amplitude drastically increased in the 1970s and the 1980s at the Finnish coasts, and decreased again at the end of the twentieth century. Also, the short-term water level variability had a local minimum in the 1960s, increased until the 1980s, and then decreased until the end of the century (Johansson et al. 2001). The mismatch of the changes of the wind, wave, and water level dynamics in the northern Baltic Proper is a highly interesting feature and needs further investigation.

The qualitative match of the long-term variations of average wave properties at Almagrundet and at Vilsandi proves that decadal changes in the dominating wind directions cannot cause such long-term changes. Consequently, variations of certain other properties of the wind fields such as the duration of winds from different directions or changes in wind patterns related to the shifts of the trajectories of cyclones (Suursaar et al. 2006) may play a crucial role in the forming of long-term variations of the Baltic Sea wave fields.

Extreme wave conditions with $H_S \geq 7$ m were first observed in January 1984 in the northern Baltic Sea. Later on such seas occurred probably 1–2 times in late 1980s, once in 1990–1995, and four times since 1996. The frequency of extreme wave storms, therefore, has been largely unchanged during the last 30 years: they occur roughly twice a decade.

The strong reaction of the water surface is the most interesting feature of windstorm Gudrun that excited very high and long waves, although the maximum sustained wind speed was not exceptional and the wind direction was not particularly favourable for wave generation. Wave conditions with $H_S \sim 9.5$ m are much rougher than could be expected, based on the existing wave statistics (Lopatukhin et al. 2006a, b). Remarkably, long and high waves also appeared in the interior the Gulf of Finland, in an area which generally is sheltered from long waves. Given the rapid decrease of the mean wave height in 1997–2005, this event suggests that the decrease is accompanied by certain nontrivial changes of the forcing patterns.

It might be speculated that a future storm of the same strength and duration, but corresponding to more favourable wave generation conditions (e.g., a strong and large cyclone travelling in the NNE direction), may create even higher waves. Since only a few cyclones do so (Suursaar et al. 2006), such a 'perfect storm' is not likely to occur. However, if it did happen, it probably would excite even rougher wave conditions at the entrance of the Gulf of Finland and off the south-western coast of Finland than Gudrun did near Saaremaa. The possibility of such rough seas within the existing climatological conditions is of paramount importance for navigational safety and design of offshore structures.

The future climate changes are quite likely to modify factors controlling the volume of the water body, the mean temperature, salt water inflow conditions, the overall transport scheme of waters, the distribution of upwelling and downwelling patterns, the location of areas of the largest wave intensity and wave-induced mixing (Myrberg et al. 2007), and therefore the vertical and horizontal distribution of salinity, temperature, and other decisive constituents of the local ecosystem. In particular, the increased sea surface temperature leads to the reduction of ice cover in the northern parts of the sea. The potential increase of wind stress at sea-surface during relatively windy winter months may lead to further changes of wave climate; in particular, to enhancing of the extremes in wave heights and sea levels. Timely detection of such changes is a major challenge for scientists. Launching of adaptation measures is an accompanying challenge of decision-makers.

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