Extremes and Decadal Variations in the Baltic Sea Wave Conditions

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Abstract Average and extreme wave conditions, their seasonal cycle and decadal variations, and extreme wave storms in Baltic Sea Proper and in the largest sub-basins of this sea are studied based on long-term time instrumentally measured time series of wave properties at Almagrundet and the Darss Sill, visual wave observations from several coastal sites of the eastern Baltic Sea, wave statistics from the northern Baltic Proper and Gulf of Finland, long-term reconstructions of the wave climate and numerical modelling of an extreme wave storm. The wave climate is highly intermittent and occasionally contains very strong wave storms. Significant wave heights $H_S \geq 4$ m occur with a probability of about 1 % among all wave fields in the open Baltic Proper. Extreme wave conditions with $H_S \geq 7$ m occur approximately twice in a decade. The overall recorded maximum H_S is 8.2 m. The estimated maximum of H_S was about 9.5 m in cyclone Gudrun in January 2005. No clear trend exists in the wave properties in the Baltic Sea. The 99 %-iles of the significant wave height exhibit a complicated spatial pattern of changes and have significantly decreased between the islands of Öland and Gotland and to the south of these islands.

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. Feistel et al. 2008; Leppäranta and Myrberg 2009). The combination of a relatively small size of this water body and vulnerability of its ecosystem makes this region extremely susceptible with respect to climate changes and shifts. Its complex geometry, high variability of wind patterns and extensive archipelago areas with specific wave propagation properties (Tuomi et al. 2014) give rise to large spatio-temporal variability in the wave properties. The presence of relatively shallow areas and often occurring convergent wind patterns may lead to occasional wave energy concentration in some areas (Soomere 2003, 2005; Soomere et al. 2008). This feature requires a high

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spatial resolution of wave simulations and also a careful choice of wave measurement sites. The seasonal ice cover of large parts of the sea considerably affects the wave patterns during winter and early spring. As wave measurement devices are removed well before the ice season (Kahma et al. 2003; Tuomi et al. 2011), the wave data have long gaps and several commonly used characteristics (e.g. annual mean wave height or period) may become meaningless (Tuomi et al. 2011). The situation is additionally complicated by specific features of wave generation by offshore winds over irregular coastline (Kahma 1981; Kahma and Calkoen 1992) or under so-called slanting fetch (when wind blows obliquely across the coastline; Pettersson et al. 2010).

Numerous changes in the forcing conditions and in the reaction of the water masses of the Baltic Sea have been reported during the later decade (BACC Author Team 2008, BACC II Author Team 2015). The apparently increasing storminess in the Baltic Sea during the second half of the 20th century (Alexandersson et al. 1998) has caused extensive erosion of depositional coasts (Orviku et al. 2003). The changes in the average wave climate of the entire Baltic Sea and adjacent seas have been found marginal, at least, until the mid-1990s (WASA Group 1995; Mietus and von Storch 1997).

Very rough seas that occurred twice in December 1999, all-time highest significant wave height 8.2 m in the Baltic Proper in December 2004 (Tuomi et al. 2011) and all-time highest single wave in the Gulf of Finland in November 2012 (9.4 m, www.fmi.fi), reinforced the discussion as whether the wave conditions in the Baltic Sea have become rougher compared with the situation a few decades ago. The exceptional storm Erwin/Gudrun (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). Recent numerical simulations (Soomere and Räämet 2011a, b; Tuomi et al. 2011), analysis of long-term directional wave measurements in the Arkona Basin (Soomere et al. 2012) and reconstructions of the nearshore wave climate back to the mid-1940s based on visual wave observations (Soomere 2013) have shed much more light on spatio-temporal variations in the Baltic Sea wave climate.

Recognition of the wave climate changes, in particular, changes in 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 a reliable wave climatology for open ocean conditions, based on 6-hourly means of wave properties over an average of $1.5° \times 1.5°$ areas. This resolution is too sparse for the Baltic Sea conditions. As typical for semi-enclosed shallow basins, wave properties are additionally modified here through wave-bottom interaction (refraction, shoaling, breaking or reflection) and diffraction behind obstacles.

The Baltic Sea has probably the longest history in the world of almost one and half centuries of systematic visual observations of wave properties from fixed coastal locations (Rosenhagen and Tinz 2013). Similar observations from lightships started about 90 years ago in Danish waters (Hünicke et al. 2015) and slightly later in Swedish waters (Wahl 1974). Systematic observations of wave properties from many coastal sites were launched in the eastern Baltic Sea since the mid-1940s, and such observations are performed at a few sites until today (Soomere 2013). The outcome of these historical observations combined with similar data from ships and results of various early hindcasts has been formulated in several generations of textbooks (Davidan et al. 1978, 1985; Lopatukhin et al. 2006b) and wave atlases for the Baltic Sea (Rzheplinsky 1965; Russian Shipping Registry 1974; DWD 2006; Lopatukhin et al. 2006a) and its sub-basins (Druet et al. 1972; Rzheplinsky and Brekhovskikh 1967; Schmager 1979; Sparre 1982).

The properties of wind waves primarily depend on the wind speed and duration, and effective fetch length. The pattern of predominant 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 (Schmager et al. 2008). 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.

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. Numerical reconstruction of the Baltic Sea wave fields is still a complicated task, and the results usually contain extensive uncertainties (Cieślikiewicz and Paplińska-Swerpel 2008; Kriezi and Broman 2008; Räämet et al. 2009). The largest source of uncertainties is the wind information (Nikolkina et al. 2014). Its quality has considerably increased within the last decade, but this information still suffers from substantial temporal inhomogeneity (Tuomi et al. 2011), spatial variations in its quality (Räämet et al. 2009; Soomere and Räämet 2011b), and occasional mismatch of modelled and actual air flow directions (Keevallik and Soomere 2010).

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; Siewert et al. 2015). Early estimates of wave statistics for the entire Baltic Proper have been performed using the second-generation spectral wave model HYPAS and wind data from a few years (1999–2000; Jönsson et al. 2003, 2005; Danielsson et al. 2007). Although third-generation wave models such as WAM (e.g. Komen et al. 1994) and SWAN 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 was available only for limited areas until 2005 (Soomere 2003, 2005). Extensive simulations based on different wind information were performed only starting from about 2005 (Schmager et al. 2008; Soomere and Räämet 2011a, b; Tuomi et al. 2011). These simulations together with the increasing pool of instrumental measurements (Tuomi et al. 2011; Soomere et al. 2012) and reconstructions of wave properties from historical visual observations (Zaitseva-Pärnaste 2013) made it possible to identify not only the basic properties of the wave climate of the Baltic Sea (Hünicke et al. 2015) but also to distinguish a remarkable pattern of its spatial and decadal variations (Soomere and Räämet 2011b, 2014; Suursaar 2013).

This chapter presents a description of the basic properties of average and extreme wave conditions and depicts their spatio-temporal variations in the Baltic Proper based on available long-term wave measurements (both instrumental and visual), numerical reconstructions of wave climate and wave properties in 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) and Arkona Basin are frequently connected with those in the Proper, and are addressed to some extent as well.

The analysis is mostly based on (i) instrumental measurements in 1978–2003 at Almagrundet (located near the western coast of the northern Baltic Proper), in 1990–2011 at the Darss Sill in the Arkona Basin, since 1996 in the northern Baltic Proper and since 2001 in the Gulf of Finland, (ii) visual observations from 12 sites along the eastern coast of the Baltic Sea from the vicinity of Kaliningrad to the neighbourhood of Saint Petersburg and (iii) numerical reconstructions of the entire Baltic Sea wave fields using geostrophic winds and the outcome of HIRLAM model. To a limited extent, data from waveriders in the northern Baltic Proper and at 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 Long-Term Wave Measurements and Hindcasts in the Baltic Sea

2.1 Instrumental Data Sets

Contemporary instrumental 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).

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 the region. 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 predominant winds. The fetch length for winds from the south-west, west and north-west is quite limited. 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 for some wind directions (Kahma et al. 2003).

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

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

The set of 95 458 measurements using the Simrad device in 1978–1995 reliably describes the wave properties (Broman et al. 2006). Later 46 671 recordings using the WHM device in 1993–2003 have certain quality problems: the data contain a number of modest, but still evidently unrealistic peaks and the values of wave period are unreliable. Broman et al. (2006) recommend considering the WHM data for 1993–2003 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 during total 14 630 h, or about 2 years of uninterrupted measurements. The data set is concentrated in the autumn season and thus represents the wave climate during relatively windy months.

A directional waverider was deployed in the northern Baltic Proper at a depth of about 100 m (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). This data set is the most representative of the northern Baltic Sea wave fields; however, only its few sections have been analysed in the literature.

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, 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). Similar wave measurements have been performed almost continuously since 29 January 1991 at a 20-m-deep site on the Darss Sill (Soomere et al. 2012; 54°41.9′N, 12°42.0′E). This data set together with similar measurements since 2002 to the north-west of Cape Arkona (54°52.9′N, 13°51.5′E) forms the most valuable source of the wave information in the SW Baltic. Some elements of the wave climate in the southern and south-eastern Baltic Sea have been presented in (Paplińska 1999; Cieślikiewicz and Paplińska-Swerpel 2008; Siewert et al. 2015).

The number of contemporary wave measurement locations has increased in the Baltic Sea since 2006 (Pettersson et al. 2007). The main results are described on annual basis on the HELCOM website http://helcom.fi/baltic-sea-trends/environment-fact-sheets/hydrography/wave-climate-in-the-baltic-sea/. Instrumentally measured wave

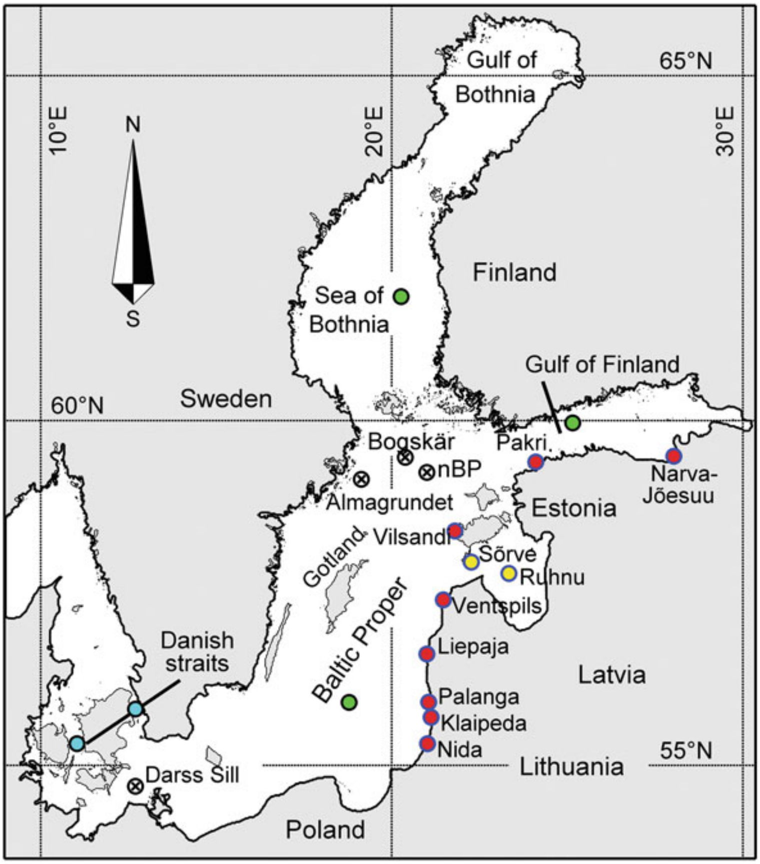

Fig. 1 Location scheme of the Baltic Sea, showing the sites of instrumental measurements discussed in detail in this chapter (*crossed circles*), sites of directional waveriders in the southern Baltic Proper, Gulf of Finland and Sea of Bothnia (*green circles*) and visual wave observation sites at the eastern coast of the Baltic Sea (*red circles*) and in the Gulf of Riga (*yellow circles*)

data from the coastal areas of Estonia, Latvia and Lithuania have been mostly obtained using pressure-based sensors (Soomere 2005) or ADCP-s (Suursaar 2013), and cover only shorter sections of a few months. Satellite altimeter data for wave properties have been used in a very few studies (Cieślikiewicz and Paplińska-Swerpel 2008; Tuomi et al. 2011).

2.2 Visual Observations

A reasonable source of the open-sea wave information in the past formed visual observations (Davidan et al. 1985; Hogben et al. 1986). The visually observed wave height generally matches the significant wave height well (Gulev and Hasse 1998, 1999). The visually estimated wave periods are, on average, a few tenths of a second shorter than the peak period (Gulev and Hasse 1998, 1999). Wave climate changes estimated from data observed from merchant ships are consistent with those shown by the instrumental records (Gulev and Hasse 1999; Gulev et al. 2003).

Visual observations from the coast are less frequently used for wave climate studies. Such data frequently represent only wave properties in the immediate vicinity of the observation point (Orlenko et al. 1984; Soomere 2005). They pose intrinsic quality and interpretation problems, contain a large fraction of subjectivity (Zaitseva-Pärnaste et al. 2009), have a poor temporal resolution, have many gaps caused by inappropriate weather conditions or by the presence of ice, may give a distorted impression of extreme wave conditions, etc. 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). These data sets have, however, exceptional temporal coverage for the Baltic Sea. Regular wave observations have been performed using a unified procedure at many locations since the mid-1940s during up to almost 70 years (Zaitseva-Pärnaste et al. 2011; Pindsoo et al. 2012) and are thus one of the few sources for detecting the long-term alterations of the wave climate. These observations have been carried out usually 3 times per day using perspectometers (binoculars with a specific scaling), buoys or bottom-fixed structures to better characterise the wave properties. 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 Räämet 2011b).

The observers scanned at least 4-m-deep areas about 200–400 m from the waterline. To evaluate the wave height, the observer noted the five highest waves during a 5-minute time interval and filed the highest single wave $H_{\max}$ and the mean height H_{mean} of these waves. The visually observed wave height, obtained using this or similar procedure, tends to overestimate the wave heights as the observer often picks up the largest waves and not necessarily in a single location. There have been many efforts to link the visually observed wave heights with the instrumentally measured ones (Massel 2013). As the typical wave periods in the coastal zone of the Baltic Sea are 3–4 s (Broman et al. 2006; Zaitseva-Pärnaste et al. 2011), $H_{\max}$ is approximately equal to the average height of 2.5–3 % of the highest waves and the mean wave height H_{mean} is approximately equal to the average height of 5–7 % of the highest waves (Zaitseva-Pärnaste 2013). Consequently, $H_{\max}$ roughly represents the 97.5 %-ile of single wave heights and H_{mean} exceeds the significant wave height by 15–20 %. This conjecture matches the outcome of a comparative analysis of the visually observed data from lightships and instrumentally measured data. In the south-western Baltic Sea, $H_S \approx 0.94 H_{mean}$, and in the Bay of Bothnia, $H_S \approx 0.81 H_{mean}$ (Wahl 1974).

The mean height H_{mean} has usually the largest coverage in the visually observed data sets (Zaitseva-Pärnaste et al. 2011; Pindsoo et al. 2012; Eelsalu et al. 2014). As the routine of observations has been slightly changed over decades (Eelsalu et al. 2014), during some time, only $H_{\max}$ is available in the observation diaries. In these occasions, $H_{\max}$ is used to evaluate the average wave properties over longer time intervals. As the average difference between H_{mean} and $H_{\max}$ is about 6 % (Soomere and Zaitseva 2007), doing so apparently has a fairly minor influence on climatological values of wave heights.

The wave direction was visually identified with a resolution of 45° (so-called eight rhumb system) as the direction from which the waves approached. The wave period was found as an arithmetic mean from three consecutive observations of passing time of 10 waves each time. These waves were not necessarily the highest ones. There exist different opinions about the interrelations of visually observed and instrumentally measured wave periods (Guedes Soares 1986; Massel 2013). The mismatches can be often reduced to different definitions of the wave period in different observation routines (Massel 2013). Davidan et al. (1985) found that for periods <7 s (which is the case in the Baltic Sea) the visually observed wave periods (using the above-described routine) almost exactly matched the average wave periods from the zero-crossing analysis.

The visual observation conditions vary considerably along the eastern Baltic Sea coast. For example, at Pakri the observer was located on the top of a 20-m high cliff and the water depth of the area over which the waves were observed was 8–11 m (Zaitseva-Pärnaste et al. 2009). Contrariwise, at Vilsandi, the observation site was chosen from two options according to the approaching wave directions and the water depth in the observation areas was only about 4 m (Soomere and Zaitseva 2007).

All coastal sites in Fig. 1 only conditionally represent the open-sea wave conditions. The largest distortions are evidently due to the sheltering effect of the mainland and the relatively shallow water depth. It is still likely that long-term variations and trends in the offshore wave properties are evident in the coastal observations (Soomere and Räämet 2011b). In northern locations, only 1–2 observations per day were possible in autumn and winter. Most of the gaps in the data sets occur from January to March apparently owing to the presence of sea ice. To eliminate the bias caused by a varying number of observations per day, the analysis has mostly been performed using the set of daily mean wave heights or measurements at a single observation time (Soomere and Zaitseva 2007; Zaitseva-Pärnaste et al. 2009, 2011; Pindsoo et al. 2012).

2.3 Long-Term Wave Hindcasts

The relatively small size of the Baltic Sea, frequent large-scale homogeneity in the wind fields and the short reaction and saturation time and memory of wave fields

(Soomere 2003) allow to use greatly simplified wave hindcast schemes (Soomere 2005), high-quality wind data from a few points (Blomgren et al. 2001) or parametric wave models (Suursaar and Kullas 2009a, b; Suursaar 2010, 2013) to reproduce the local wave statistics. The use of such models for the identification of extreme wave conditions is limited as they basically rely on the properties of the local wind field. Several attempts have been made to perform long-term numerical reconstructions of the entire Baltic Sea wave fields, but the relevant publications are scarce and often concentrated on the used methods (Cieślikiewicz and Paplińska-Swerpel 2008; Kriezi and Broman 2008; Alari 2013). The main features of the wave climate and its possible changes in this water body were established using simulations for 1958–2002 based on the output of National Centres for Environmental Prediction and for Atmospheric Research (NCEP/NCAR) wind reconstructions (Augustin 2005) and depicted in (Schmager et al. 2008; Weisse and von Storch 2010).

A more detailed description of the Baltic Sea wave climate was produced for 1970–2007 using the WAM wave model (Komen et al. 1994) Cycle 4 forced by adjusted geostrophic winds (Räämet and Soomere 2010; Soomere and Räämet 2011b). The bathymetry for the model run was based on the so-called Warnemünde data set of water depths for the Baltic Sea (Seifert et al. 2001). The calculation was carried out over a regular rectangular grid with a resolution of about 3 nautical miles. The grid covers the area from 09°36′E to 30°18′E and from 53°57′N to 65°51′N and contains 239 × 208 points (11 545 sea points). It was cut off in the narrowest part of the Danish straits, and the model was run independently from the North Sea. The entire grid was optimised for wave calculations, e.g. deeply indented bays were omitted (Soomere 2003) and very large bottom gradients at a few locations were smoothed. The run was performed in shallow water mode with depth refraction but without depth-induced wave breaking. The presence of sea ice was ignored. Doing so may substantially modify the average and extreme wave properties in the northern sub-basins of the Baltic Sea (Tuomi et al. 2011). The energy spectrum contained 24 equally spaced directions at each sea point. The range of wave frequencies was extended to properly resolve the wave growth under relatively low winds and short fetch. The model accounted for 42 wave components with frequencies ranging from 0.042 Hz to about 2 Hz and arranged in a geometrical progression with an increment of 1.1.

The wind data were extracted from the Swedish Meteorological and Hydrological Institute (SMHI) geostrophic wind database. The original geostrophic wind components were presented as gridded information with a spatial resolution of 1 × 1°. To derive an approximation of the 10 m level wind, the geostrophic wind vector was first rotated by 15° counterclockwise, and its length was multiplied by a factor of 0.6 to mirror the effect of surface roughness. This scheme explicitly ignores many details of the vertical structure of realistic winds (Bumke and Hasse 1989), but it is still quite popular in studies of the Baltic Sea dynamics (Myrberg et al. 2010). The resulting values were first externally interpolated to a grid with a step of about 6 nautical miles (123 × 107 points) and finally into the resolution of the WAM model internally in this model. The wind input time step was 6 h before September 1977 and 3 h after that. The calculations tend to underestimate the long-term average wave heights and

99 %-iles of the significant wave height by about 10 % (Tuomi et al. 2011) but almost exactly match the measured 95 %-iles of the significant wave height in the Arkona Basin (Soomere et al. 2012).

3 Wave Climate

3.1 Statistics of Wave Heights and Periods

The above-described sources of the information about the Baltic Sea wave fields make it possible to reliably identify the basic long-term wave properties (average and extreme wave height, typical periods, occurrence distributions of different heights

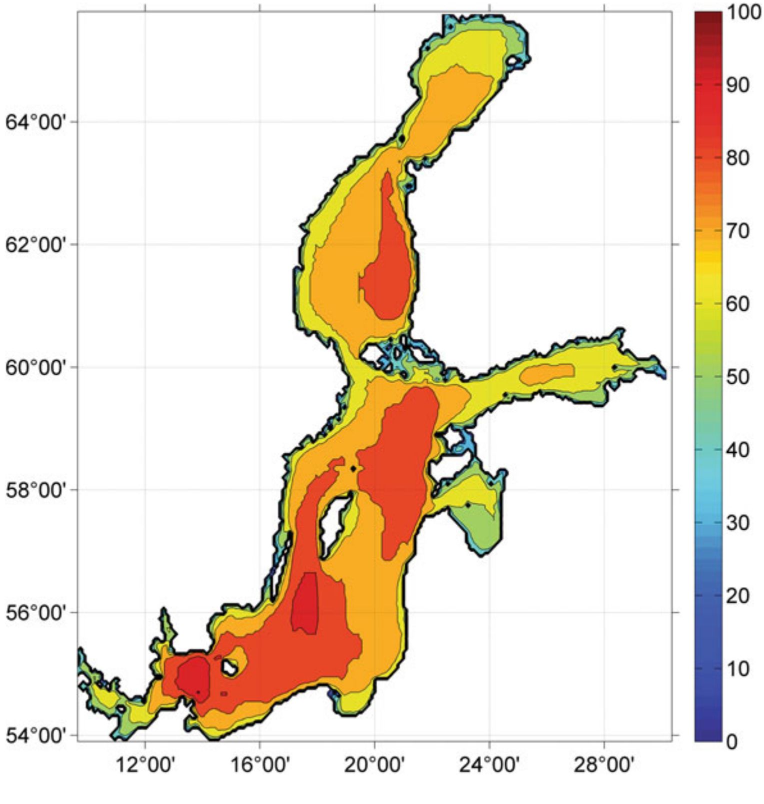

Fig. 2 Numerically simulated average significant wave height (cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007 based on adjusted geostrophic winds from the Swedish Meteorological and Hydrological Institute (Räämet and Soomere 2010). A local maximum in the Arkona Basin is evidently caused by overestimation of the 10-m wind speeds from the geostrophic wind data for this region

and periods, and height–period combinations) and their spatial variations in this water body. The wave climate of the Baltic Sea is relatively mild. As mentioned above, simulations of Räämet and Soomere (2010) (Fig. 2) apparently underestimate the long-term significant wave height (around 0.9 m in the Baltic Proper) by 10–15 %. The significant wave height in the open part of the Baltic Proper according to most of reconstructions slightly exceeds 1 m and is somewhat less between Gotland and the Swedish mainland (Kahma et al. 2003; Broman et al. 2006; Schmager et al. 2008; Tuomi et al. 2011). The differences between the various estimates of the long-term wave heights are about ±15 % and mostly stem from differences in the underlying wind fields (Nikolkina et al. 2014).

The long-term average wave heights are 0.6–0.8 m in the open parts of larger subbasins of the Baltic Sea such as the Gulf of Finland (Soomere et al. 2010; Suursaar 2013) or Arkona Basin (Soomere et al. 2012), around 0.5 m in the open part of the Gulf of Riga (Eelsalu et al. 2014) and well below 0.5 m in semi-sheltered bays such as Tallinn Bay (Soomere 2005; Kelpšaitė et al. 2009). These values are by 10–20 % lower in the nearshore regions (Suursaar and Kullas 2009a, b; Suursaar 2010; Soomere 2013) and considerably lower in these nearshore areas of larger subbasins (such as the western Gulf of Riga) that are sheltered with respect to predominant wind directions (Eelsalu et al. 2014).

The spatial patterns of average wave heights are slightly different in different hindcasts. They contain either an elongated maximum (Augustin 2005, Tuomi et al. 2011) or several local maxima in the eastern Baltic Proper (Jönsson et al. 2003). The calculations of Räämet and Soomere (2010) based on geostrophic winds suggest that another maximum may exist to the south of Gotland. This disparity may partially reflect large inter-annual and decadal variability in wind patterns over the area (Soomere and Räämet 2014) but more likely it indicates inconsistency of forcing wind fields (Nikolkina et al. 2014).

The probability distributions of the occurrence of different wave heights at open-sea measurement sites (Almagrundet, Bogskär, northern Baltic Proper, Arkona Basin) resemble a Rayleigh distribution (Fig. 3) with typical values of the shape parameter of 1.5–1.8 (Soomere et al. 2011). The median wave heights are about 20 % and the most frequent wave heights (usually in the range of 0.5–0.75 m) up to 30 % lower than the long-term average wave height (Kahma et al. 2003; Soomere et al. 2008, 2012). This distribution for visually observed data sets has a distinguished peak for very low wave heights and calms, and resembles analogous distributions for wave heights in semi-sheltered bays of the Baltic Sea (Soomere 2005). The excess proportion of calms in the data sets of visual observations (often >30 %, Soomere and Zaitseva 2007; Zaitseva-Pärnaste et al. 2009, 2011; Pindsoo et al. 2012) evidently is due to the absence of observable waves in many cases of easterly winds. Removing a fraction of calms from these sets therefore is roughly equivalent to ignoring the observations that inadequately reflect the open-sea wave fields in such wind conditions. For example, if the number of calms is reduced to 6 % from the total number of recordings (which is the level typical for the northern Baltic Proper, Fig. 2), the average wave height for wave systems propagating onshore at Vilsandi is 0.74 m (Soomere and Zaitseva 2007).

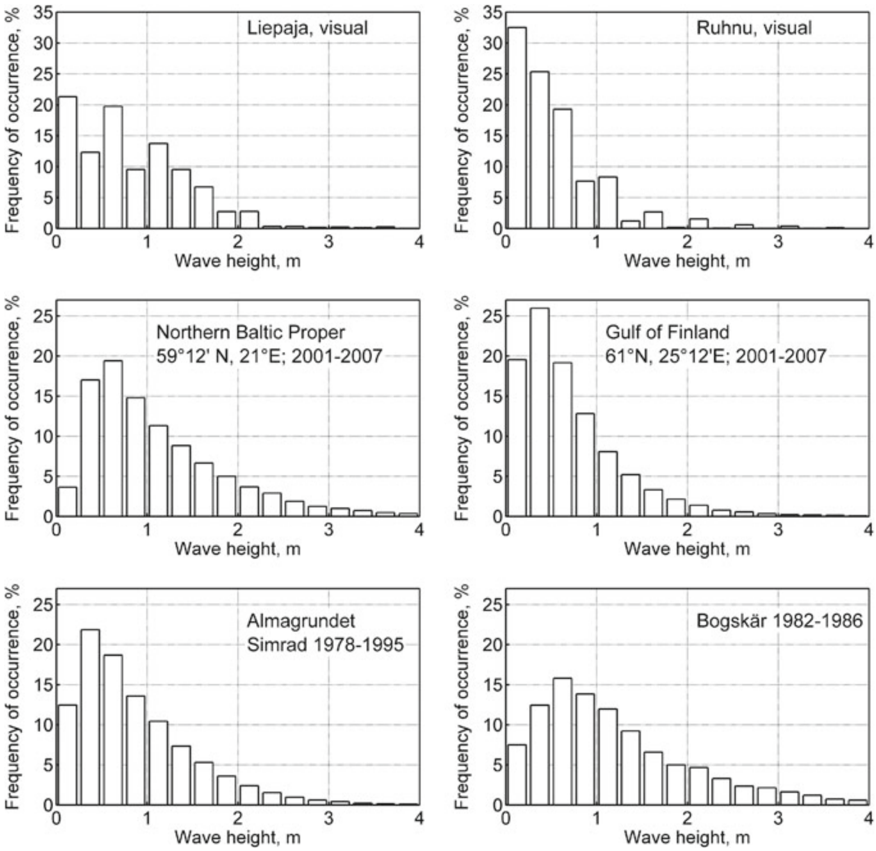

Fig. 3 Frequency of occurrence of wave heights at Almagrundet 1978–1995 (Broman et al. 2006), Bogskär 1982–1986 (Kahma et al. 2003), according to the hindcast for 2001–2007 in the northern Baltic Proper and in the Gulf of Finland (Tuomi et al. 2011), and according to visual observations at Liepaja and Ruhnu (Pindsoo et al. 2012; Eelsalu et al. 2014)

Most frequently waves with periods of 4–6 s dominate in the middle of the Baltic Proper, whereas in the more sheltered and coastal regions, waves with periods of 3–4 s predominate (Fig. 4). Periods up to 7–8 s are also common on the open sea. This difference in periods apparently comes from a relatively large number of short-fetched waves at sheltered measurement sites. A large proportion of the combinations of wave heights and periods roughly correspond to saturated wave fields with a Pierson–Moskowitz (PM) spectrum (Soomere et al. 2008; Räämet et al. 2010; Soomere et al. 2011). Such wave systems generally occur in the Baltic Sea at wind speeds up to about 8 m s^{-1} (Schmager et al. 2008). The properties of the roughest seas, however, match better a JONSWAP spectrum. These wave fields correspond to fetch-limited seas and are characterised by shorter periods (equivalently, they are steeper) than wave fields with a PM spectrum. Fetch-limited seas are typical in more

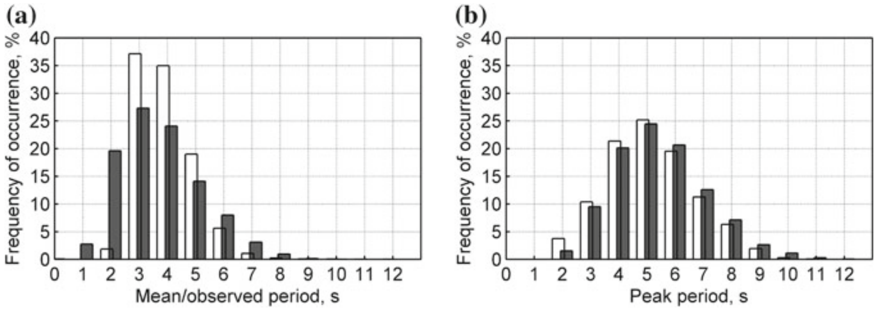

Fig. 4 Frequency of occurrence of wave periods: **a** Almagrundet 1978–1995 (*white bars*, Broman et al. 2006) and Vilsandi 1954–2005 (*filled bars*, Soomere and Zaitseva 2007), **b** Bogskär 1982–1986 (*white bars*) and the northern Baltic Proper 1996–2000 (*filled bars*, Kahma et al. 2003)

sheltered areas such as the Darss Sill (Soomere et al. 2011). The proportion of intense swells is very limited in all parts of the Baltic Sea.

The joint distributions of wave heights and periods (Fig. 5) 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 have a typical height of about 1 m. Periods 6–7 s commonly 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 $T_m > 8$ s (peak periods $T_p \geq 10$ s) dominate either in very rough seas (wave heights >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 stage of the January 1984 storm when $H_{1/3} \sim 7$ m, the mean period was below 10 s. The waverider in the northern Baltic Proper registered the peak period of about 12 s about twice a year and at Bogskär roughly once in 2 years (Kahma et al. 2003).

3.2 *Extreme Conditions*

The Baltic Sea wave climate is highly intermittent. The sea occasionally hosts furious wave storms in certain seasons when the conditions are favourable for the generation of high waves. The highest waves in this water body are, however, much smaller than in the open ocean. Rough seas with the wave heights over 4 m occurred with a probability of 0.42 % in 1978–1995 at Almagrundet, of 1 % at Bogskär, and of 1.4 % in the northern Baltic Proper. Such seas usually occur several times a year, each time during a few hours. The area in which the significant wave height may exceed 4 m within 1 % of time (equivalently, the 99 %-ile of the wave height exceeds 4 m) is almost fully located to the east of the geometrical centreline of the Baltic Proper

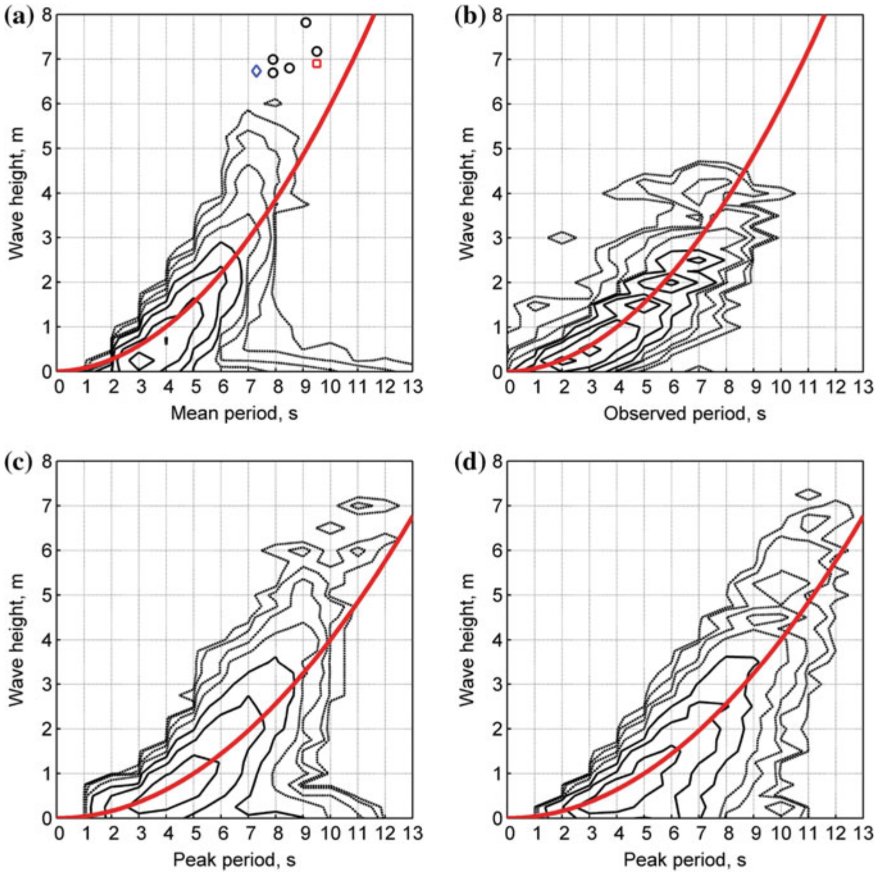

Fig. 5 Joint distribution of wave heights and periods: **a** Almagrundet 1978–1995 (Broman et al. 2006), **b** Vilsandi 1954–1994 (Soomere and Zaitseva 2007), **c** Bogskär 1982–1986, **d** northern Baltic Proper (Kahma et al. 2003). The wave height step is 0.25 m, and the period step is 1 s. The range 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* in panels **c** and **d** indicates the relationship $H_S = g\sqrt{\alpha/5}/\pi^2 \times T_p^2 \approx 0.04T_p^2$ between the significant wave height and peak period for saturated wave conditions with a Pierson–Moskowitz spectrum corresponding to the classical value $\alpha = 0.0081$. Similar lines in panels **a** and **b** assume that the mean period is about 80 % of the peak period

(Tuomi et al. 2011). Wave heights exceed 6 m with a probability of 0.1 % (8.8 h yr^{-1}) almost in the same area.

Seas in which $H_S > 7$ m are extremely rough in the Baltic Sea basin. Waves of this height cannot be observed from coastal observation stations because of the limited depth at all sites. This threshold was not reached at Bogskär in 1982–1986. The significant wave height >7 m has been recorded only five times in the northern Baltic Proper since 1996: twice in December 1999, on 22 December 2004, on 9 January 2005 during windstorm Gudrun (Soomere et al. 2008) and in December 2011 (Pettersson et al. 2012). The peak periods during these events slightly exceeded 12 s. Similar wave heights have been recorded twice in the southern Baltic at 55°55′N, 18°47′E (7.4 m on 14 October 2009 and 7.2 m in February 2011, Pettersson et al. 2010, 2012).

The largest instrumentally measured significant wave height $H_S = 8.2$ m occurred in the northern Baltic Proper on 22 December 2004. The highest single wave reached 14 m (Tuomi et al. 2011). It took thus 20 years to overshoot the previous maximum. It was set by a ferocious storm at Almagrundet on 13–14 January 1984 when $H_{1/3}$ calculated using Eq. (1) reached 7.82 m and the highest single wave was 12.75 m high[1] (Broman et al. 2006). An alternative estimate of the significant wave height in this storm from wave spectrum was $H_S = 7.28$ m. The wave periods remained fairly modest ($T_m = 9.1$ s, $T_p = 10.7$ s, Broman et al. 2006). This was the only case during which $H_{1/3} \geq 7$ m was registered at Almagrundet. Instrumentally measured extreme wave heights are generally lower in the southern Baltic Sea. This is evidently caused by the lack of wave measurement devices in this part of the Baltic Sea that, according to hindcasts, should host as severe extreme waves as the northern Baltic Proper. As mentioned above, a significant wave height >7 m has been measured only twice in the southern Baltic Sea.

3.3 The Ratio of Extreme and Average Wave Heights

In many coastal engineering applications, it is implicitly assumed that the ratio of the extreme and average wave heights is approximately constant. This assumption is used, for example, in express estimates of the closure depth of (almost) equilibrium beach profiles. This depth indicates the water depth until which storm waves substantially and regularly affect the shape of the coastal profile (Kraus 1992; Dean 1991). It is a widely used concept in coastal engineering and a fundamental variable in modelling of coastal evolution and morphology. It basically depends on the roughest wave conditions that persist for a reasonable time at a given site (Hallermeier 1981).

[1] The Almagrundet data set from 1993–2003 contains several contradicting extreme wave records. A severe storm in March 1997 that affected nearly the whole Baltic Proper caused $H_{1/3} = 7.83$ m. As 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 but the significant wave height, estimated from the wave spectrum, was only 3.8 m. The listed values are apparently doubtful although they do represent quite severe wave fields (Broman et al. 2006), and the value of $H_{1/3}$ in December 1996 is consistent with the data from the waverider in the northern Baltic Proper. More reliable are the data from 1978–1995. 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. 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.

A convenient measure of the severest part of the wave climate in this respect is the significant wave height $H_{0.137}$ that is exceeded during 12 h in a year, that is, with a probability of 0.137 % (Hallermeier 1981). The simplest approximation for the closure depth h_c as a linear function is $h_c \cong q_1 H_{0.137}$. The commonly used values are $q_1 = 1.5$ (Birkemeier 1985) and $q_1 = 1.57$ (Hallermeier 1981). Houston 1996 extended this relationship towards the use of the long-term significant wave height H_{mean} as $h_c \cong q_1 H_{0.137} \cong q_2 H_{mean}$ and evaluated that $q_2 = 6.75$. It is, however, not necessarily correct for areas with a specific wave climate as it implicitly assumes the relationship $H_{0.137} \cong 4.5 H_{mean}$. This relationship has been established for wave fields with a Pierson–Moskowitz spectrum that is common for the observed wave statistics along the US coasts (Houston 1996).

The proportions of the mean and extreme wave heights are different in semi-enclosed seas like the Baltic Sea where intense swells are almost absent and windseas carry a large part of the wave energy. As discussed above, a specific feature of the Baltic Sea wave climate is that the average wave conditions are relatively mild but very rough seas may episodically occur in long-lasting severe storms (Soomere 2005; Broman et al. 2006; Soomere et al. 2012). Waves in such storms are much higher than expected from the mean wave conditions. This feature leads to a marked difference between the factor q_2 used in $h_c \cong q_2 H_{mean}$ for the open ocean coasts and its analogue for the Baltic Sea. The typical ratio of these two measures for the coasts of the open Baltic Proper is $H_{0.137}/H_{mean} \cong 5.5$ (Soomere et al. 2013). This result suggests that an appropriate express formula for the closure depth in the Baltic Sea conditions is $h_c^B \cong 1.5 H_{0.137} \cong 8.25 H_{mean}$, while the above expression with $q_2 = 6.75$ is valid for short relatively sheltered sections of the Baltic Sea shore located in bayheads.

3.4 Sub-basins of the Baltic Sea

The average and, in particular, the maximum wave heights in the semi-sheltered sub-basins of the Baltic Sea 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) largely mimic the changes in the open-sea winds (Soomere 2005).

The largest wave heights among the major sub-basins of the Baltic Sea occur in the Sea of Bothnia where the numerically simulated maxima of H_S exceed 7 m (Tuomi et al. 2011) and may reach 7.6 m (Soomere and Räämet 2011b). The maximum significant wave height 6.5 m has been measured in this water body on 09 December 2011 (Pettersson et al. 2012).

Based on data from 1990–1991 to 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 were thought to occur extremely seldom (Alenius et al. 1998; Pettersson 2001). The peak periods in rough seas (with $H_S \sim 4$ m) were 8–9 s (Kahma and Pettersson 1993). Recent data show that considerably rougher seas may occur in this gulf. In November 2001, seas with $H_S = 5.2\,\mathrm{m}$ and $T_p \approx 11\,\mathrm{s}$ occurred (Pettersson and Boman 2002). The same significant wave height (Pettersson et al. 2013) and the all-time highest wave of 9.4 m (www.fmi.fi) were measured on 30 November 2012 during an easterly storm. Wave fields with $T_p \geq 10\mathrm{s}$, however, usually correspond to a penetration of long-period swell of moderate height into the gulf. Only a few observations reveal such long periods: $T_p \approx 11\,\mathrm{s}$ 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 et al. 2010) 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. 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 et al. 2010).

The frequency of occurrence of waves with $H_S > 4\,\mathrm{m}$ is very small for all sub-basins except for the Sea of Bothnia (Tuomi et al. 2011), and waves with $H_S > 2\,\mathrm{m}$ can be considered as very severe for many semi-sheltered areas such as the Darss Sill (Soomere and Kurkina 2011; Soomere et al. 2012). The maximum H_S in the Darss Sill area was 4.47 m (wave period 6.2 s) on 03 November 1995 during a strong north-easterly storm (Soomere and Kurkina 2011). Numerical simulations indicate that H_S up to 6.2–6.7 m may occur in the region of the Darss Sill in the existing wave climate (Soomere et al. 2012). Other sub-basins (incl. the Gulf of Riga) are not covered by regular wave measurements. Still, during violent storms from unfavourable directions, even sheltered bays may experience very strong waves (Davidan et al. 1985). For instance, $H_S > 4\,\mathrm{m}$ apparently occurred in the interior of Tallinn Bay on 15 November 2001 (Soomere 2005).

4 Extremes During Windstorm Gudrun

Earlier estimates of extreme wave conditions with the use of the WAM model forced by homogeneous wind patterns suggested that the significant wave height generally does not exceed 8–8.5 m in the Baltic Proper (Soomere 2001). This estimate was confirmed by Lopatukhin et al. (2006a). Later simulations indicated that the significant wave height may reach 9.5–10 m in the north-eastern Baltic Proper at the entrance of the Gulf of Finland, to the north-west of the Latvian coast and in the south-eastern part of the sea in the Gulf of Gdańsk (Schmager et al. 2008; Soomere et al. 2008; Tuomi et al. 2011). The properties of waves in a specific region and storm event substantially depend on the match of the geometry of the particular sea area and the wind pattern in the storm (Augustin 2005; Soomere et al. 2008; Schmager et al. 2008).

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. 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 (Suursaar et al. 2006; Bengtsson and Nilsson 2007). 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 10-min average wind speed on the open sea (Fig. 6) was 28–29 $\mathrm{m\,s^{-1}}$. Forecasts released on 6–7 January predicted the windstorm maximum to hit the entrance of the Gulf of Finland. The significant wave height was forecast to exceed 10 m in the location of the waverider in the northern Baltic Proper, 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 would have been 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.

The waverider in the northern Baltic Proper (Fig. 1) adequately reflects extreme wave conditions in the case of south-western winds. The Gudrun's strongest winds were from west to west-south-west and occurred between Gotland and Saaremaa. The waverider therefore was located much to the north of the maximum of the wave storm. Even with these non-ideal conditions, 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 according to the directional waverider (Fig. 1). 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 in the vicinity of the island of Naissaar in 14-m-deep water at 59°37.1′N, 24°29.1′E and reached 4.5 m at the storm maximum. 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. 6) and well below $20\,m\,s^{-1}$ during a large part of the storm in the gulf (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 ≥600 km and the wind duration is ≥18 h (Rosenthal 1986). Although growth curves of Kahma and Calkoen (1992) suggest that somewhat shorter duration (∼15 h) and fetch (∼350 km) are sufficient for the generation of such seas, it is still probable that some other factors eventually contributed to 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 wave conditions in the Baltic Sea during windstorm Gudrun were routinely forecast by operational centres of Deutscher Wetterdienst (DWD), Danish Meteoro-

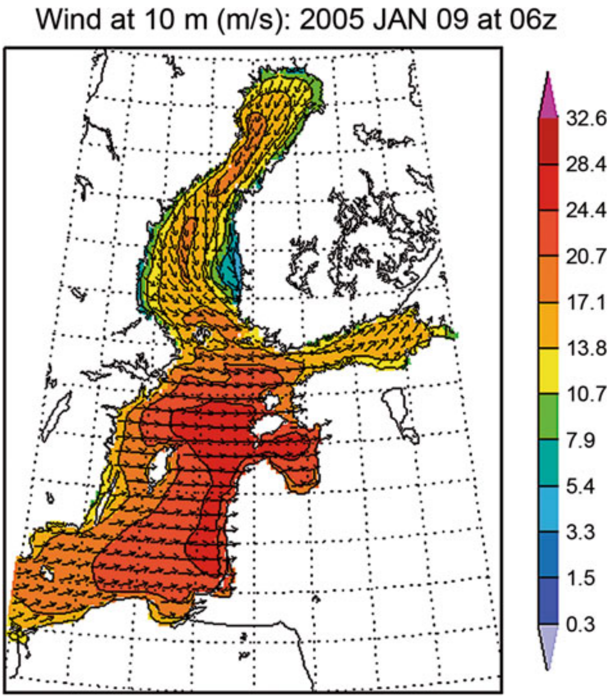

Fig. 6 Modelled wind speed ($m\,s^{-1}$) and direction (*arrows*) 10 m above water surface at 06:00 GMT on 9 January in the DMI 54-hour forecast valid at 00:00 GMT on 9 January. Courtesy of the Danish Meteorological Institute

Table 1 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 the location of the waverider in the northern Baltic Proper	Over-prediction (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

logical Institute (DMI), and Finnish Institute of Marine Research (FIMR). They all 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 used 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 were different as well (Soomere et al. 2008). The mesh size varied 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 used 24 equally spaced wave propagation directions, whereas the DMI model used 12 directions. The DWD and DMI models employed 25 frequency bands from 0.04177 in 10 % steps. The FIMR model used 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 5 strongest storms was 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 the location of the waverider in the northern Baltic Proper was overestimated by about 6 % by the FIMR model and 12–20 % by the models of the DWD and the DMI (Table 1). The wave models mostly followed the measured sea state (albeit they somewhat overpredicted the wave heights and underpredicted the wave periods) also in the Gulf of Finland (Soomere et al. 2008).

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 the relative errors of the models calculated from observed data (Table 1). 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

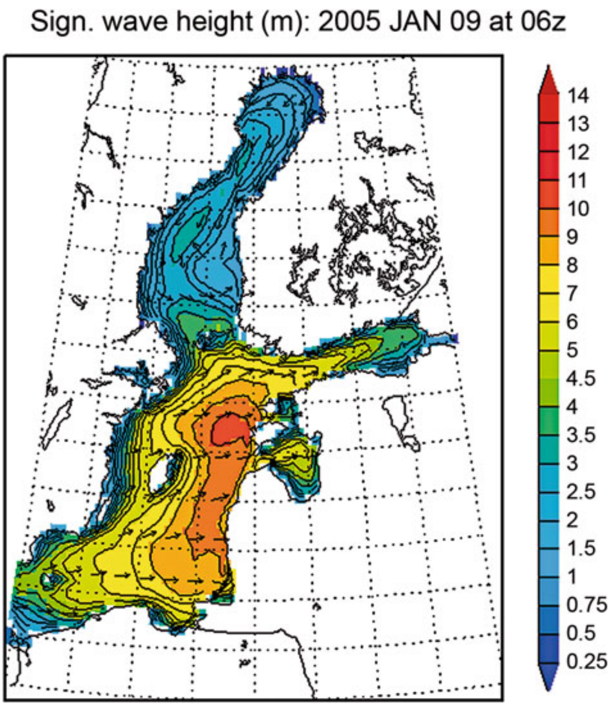

Fig. 7 Modelled significant wave heights (m) and wave propagation directions (*arrows*) at 06:00 GMT on 9 January in the DMI 54-h forecast valid at 00:00 GMT on 9 January. Courtesy of the Danish Meteorological Institute

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 of the location of the waverider in the northern Baltic Proper, off the coast of Saaremaa (about 57°N, 20.4°E, Fig. 7). This estimate was later confirmed by Tuomi et al. (2011). 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 conditionally. The significant wave height evidently reached 5 m in the gulf but most probably did not exceed the historical maximum $H_S = 5.2\,\text{m}$.

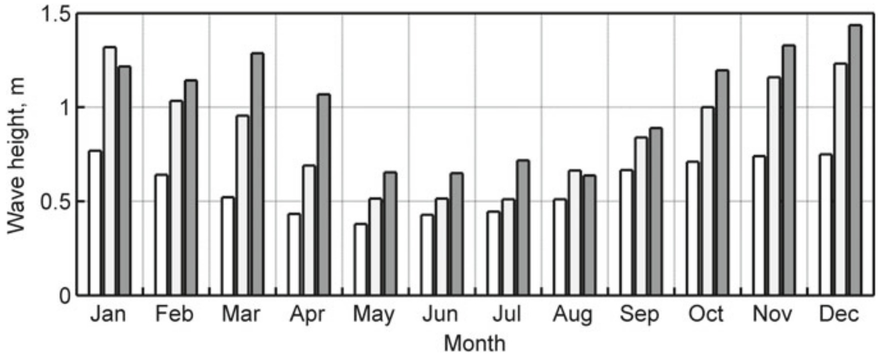

Fig. 8 Annual variation in the monthly mean wave height at Vilsandi 1954–2005 (*white bars*, based on the daily mean wave height) and at Almagrundet 1978–95 (*light grey bars*) and 1993–2002 (*dark grey bars*)

5 Seasonal, Interannual and Long-Term Variations

5.1 Temporal Variations in the Wave Heights, Periods and Directions

The extensive seasonal variation in the wind speed over the entire Baltic Sea basin (Mietus 1998) naturally causes substantial differences (by a factor of two in coastal areas and up to three times in the offshore regions) in wave heights at monthly scales (Schmager et al. 2008; Soomere and Räämet 2011b). This variation is impressive, for example, at Almagrundet, from about 0.5 m during summer to 1.3–1.4 m in winter (Fig. 8). It is much less pronounced in the data sets of visual wave observations from the coastal stations and has very limited amplitude at locations such as Sõrve (Eelsalu et al. 2014) that are sheltered from the predominant strong wind directions.

The highest monthly mean wave height occurs from October to January. Some locations reveal another minor wave height maximum, for example, in March at Almagrundet (Broman et al. 2006). It may be connected with easterly winds during late winter and early spring at the latitudes of the Gulf of Finland (Mietus 1998; Soomere and Keevallik 2003). These winds almost do not impact the wave fields in the rest of the measurement sites. The calmest period is the late spring and summer months from April to July–August.

The most intriguing question is whether any long-term changes in the extreme wave heights or their spatial patterns can be identified in the Baltic Proper. The existing visual observations reveal no long-term (∼70 yr) trend for wave heights, but the wave fields exhibit extensive trends over a few decades and substantial decadal variability. The overall course of wave activity (Fig. 9) is quasiperiodic. The interval between subsequent periods of high or low wave activity is two to three decades.

Historical visual observations suggest that there was a relatively rapid decrease in the (annual mean) wave heights in the 'pre-instrumental' era from the mid-1940s until the end of the 1970s (Soomere 2013). The further course of wave heights was different in different parts of the sea. The wave height rapidly increased in the northern Baltic Proper at a rate of 1.3–2.8 % per annum from the mid-1980s until the mid-1990s (Broman et al. 2006; Soomere and Zaitseva 2007). This increase was consistent (albeit faster) with the analogous trends for the south-western Baltic Sea and for the North Atlantic (Kushnir et al. 1997; Gulev and Hasse 1999; Vikebo et al. 2003; Weisse and Günther 2007) and also with the increase in the storminess (Alexandersson et al. 1998) and the wind speed over the northern Baltic Sea (Broman et al. 2006). The increase was followed by a drastic decrease 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). The extensive similarity of changes at Almagrundet and Vilsandi suggests that both data sets reflect certain real changes (albeit possibly overestimate their magnitude). The timing of these variations matches an almost twofold increase in the number of low- pressure observations below 980 hPa at Härnösand over the 1990s (Bärring and von Storch 2004).

The wave height at the south-eastern Baltic Sea (Lithuanian) coast showed the opposite behaviour. A rapid decrease occurred until about 1996 and a rapid increase since then (Zaitseva-Pärnaste et al. 2011). The data from Ventspils and particularly from Liepaja (Pindsoo et al. 2012) confirm that the wave height variations were fairly different in different parts of the Baltic Proper. Such changes do not necessarily become evident in all sub-basins of the Baltic Sea, for example, almost no change occurred in the annual mean significant wave height at the Darss Sill (Soomere et al.

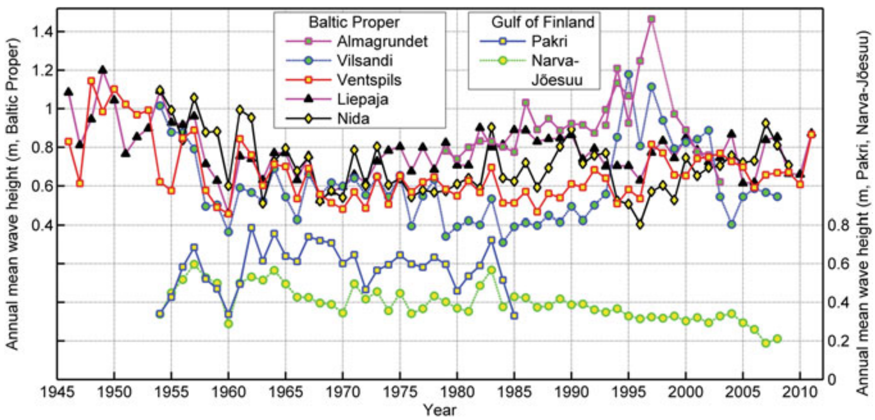

Fig. 9 Annual mean visually observed wave height at seven coastal observation sites and instrumentally measured wave height at Almagrundet (Hünicke et al. 2015). Almagrundet data from 1978 reflect only windy months November and December, and data for 1998 are missing (Broman et al. 2006). The wave heights in the mid-1990s are probably overestimated at Vilsandi

2011). Fetch-based models using one-point coastal wind have demonstrated that the wave intensity changed quasi-periodically and revealed no statistically significant trend in Estonian coastal waters (Suursaar and Kullas 2009a, b; Suursaar 2010, 2013).

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 drastic changes to the mean wave height on the background of the gradual increase in the mean wind speed (Broman et al. 2006; Räämet et al. 2009) suggest that the local wave generation conditions may have substantially changed within relatively short time intervals. Quite large variations in the average wave periods (from about 2.3 s in the mid-1970s up to 2.65 s around 1990) were hindcast for selected sites (Suursaar and Kullas 2009a, b). This change, reconstructed using fetch-based models, suggests that the wind direction may have changed.

The most prominent changes in the Baltic Sea wave fields became evident as a remarkable rotation (up to 90° from the north-west to the south-west) of the most frequently observed wave directions at Narva-Jõesuu during the last half century (Räämet et al. 2010). This change mirrors substantial changes in the local wind direction (Jaagus 2009; Jaagus and Kull 2011). Similar changes (of much smaller amplitude) observed at the Lithuanian coast were interpreted as a possible reason for changes in the distribution of erosion and accumulation areas (Kelpšaitė et al. 2011). Also, changes in the wave direction can explain certain specific features in the patterns of wave-driven sediment transport (Viška and Soomere 2012; Soomere et al. 2015).

5.2 Variations in the Wave Heights in Very Rough Seas in the Baltic Proper

Spatial variations in extreme wave heights are usually studied based on the simulated values of the 99 %-ile or the 95 %-ile of significant wave height (Schmager et al. 2008; Soomere and Räämet 2011b; Suursaar 2013). The highest extreme waves occur in the areas of the Baltic Sea with the highest overall wave intensity. The exact locations of the maxima vary in different simulations (Nikolkina et al. 2014). Most simulations agree in that the probable locations of the maxima are the south-eastern and north-eastern Baltic Proper and the eastern Sea of Bothnia (Fig. 10), that is, the areas that have the longest fetch.

There are considerable discrepancies between the results of studies into changes in the maximum wave heights. A part of the discrepancies mirrors the different natures of changes in different sea areas. Augustin (2005) identified an increase by 0.3 m in the simulated annual 99 %-ile of the significant wave height in the Baltic Proper at 58°N, 20°E. This was mostly caused by an increase in the frequency of severe wave events (BACC Author Team 2008).

Simulations over the period 1970–2007 using geostrophic winds (Soomere and Räämet 2011b) confirmed the presence of an increasing trend at this location but also brought evidence about a complex spatio-temporal pattern of changes (with scales down to about 100 km) to the Baltic Sea wave fields (Fig. 10). The pattern of changes in the extreme wave heights is almost identical to the similar pattern for the average wave heights. The most drastic decrease in the hindcast wave intensity occurred in an area between the islands of Öland and Gotland, and to the south of these islands down to the Polish coast. A probable reason for this decrease is a major rotation of the geostrophic air flow over the southern Baltic Sea from the year 1988 (Soomere and Räämet 2014; Soomere et al. 2015). The model also suggests a considerable increase in the wave activity near the coast of Latvia, between the Åland Archipelago and Sweden, and in the sea area between the Sea of Bothnia and the Bay of Bothnia. Such an increase is consistent with the outcome of fetch-based wave models based on one-point forcing (Suursaar and Kullas 2009a, b; Zaitseva-Pärnaste et al. 2009), which indicate a pronounced increase in the 90 %-ile and 99 %-ile near the Western Estonian Archipelago.

5.3 *Mismatch of Trends for the Averages and Extremes in the Gulf of Finland*

An interesting feature is the possible mismatch of the changes in the average and in the extreme wave heights (Soomere and Healy 2008) that become most contrast in the Gulf of Finland (Soomere et al. 2010; Soomere and Räämet 2011b). The

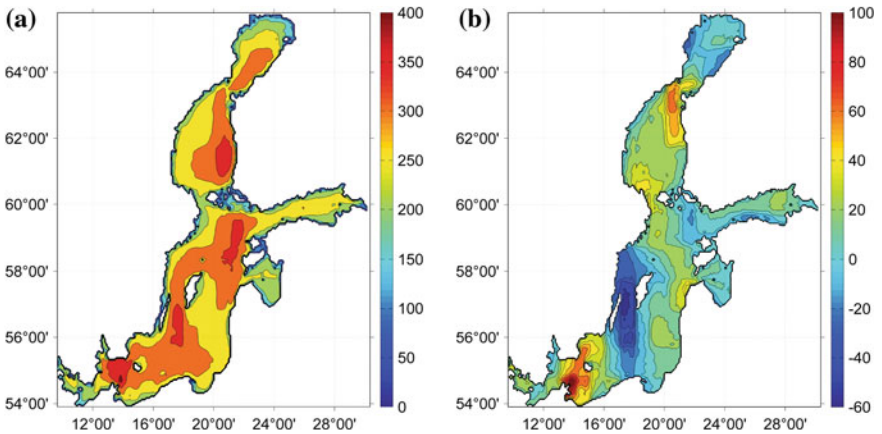

Fig. 10 **a** Numerically simulated 99 %-ile of significant wave height (cm; isolines plotted after each 50 cm) and (**b**) its linear trend in the Baltic Sea in 1970–2007 (cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007 based on adjusted geostrophic winds from the Swedish Meteorological and Hydrological Institute. Similar to Fig. 2, a local maximum in the Arkona Basin in both panels is evidently caused by an overestimation of the 10-m wind speeds from the geostrophic wind data for this region (Soomere and Räämet 2011b)

gulf is oriented obliquely with respect to predominant wind directions, and marine meteorological conditions are characterised here by remarkable wind anisotropy (Soomere and Keevallik 2003). The wind field in the gulf contains strong eastern and western winds blowing along the axis of the gulf. These winds are specific to the Gulf of Finland. They do not become evident in other parts of the Baltic Sea and are much weaker in the eastern part of the gulf. As discussed above, both average and maximum wave heights in the gulf are about 60 % of those in the Baltic Proper, whereas the wave periods in typical conditions are almost the same as in the Baltic Proper (Soomere et al. 2011).

The above-discussed changes in storminess in the northern Europe does not necessarily become evident in the interior of the Gulf of Finland, where the ageostrophic component of the surface level wind is at times substantial (cf. Keevallik and Soomere 2010). In contrast to the gradual increase in the mean wind speed over most of the Baltic Proper (Pryor and Barthelmie 2003; Broman et al. 2006), there is a very slow decrease (about $0.01\,\mathrm{m\,s^{-1}\,yr^{-1}}$) in the annual mean wind speed at Kalbådagrund (Soomere et al. 2010). Therefore, drastic long-term variations in the average wave properties are unlikely in this gulf. Consistently with this picture, numerical simulations indicate only minor changes in the annual mean wave height in the entire gulf, including its entrance area (Soomere et al. 2010).

Interestingly, Suursaar and Kullas (2009b) noted a decreasing trend in 99 %-iles near the north Estonian coast and a weak gradually increasing trend in the average wave height. Simulations using the WAM model show that, differentl from the average wave height, the maximum wave heights exhibit a clear pattern of changes since the 1970s (Fig. 11). There has been a substantial decrease (by about 10 %) in this threshold in question near the southern coast of the gulf (especially in the narrowest central part of the gulf). This is accompanied by an almost equal increase to the north of the axis of the gulf and especially in the widest sea area. The changes reach about 0.40 m, that is, up to 20 % of this wave height threshold over the 38 simulated years. Therefore, although the average wave heights have basically remained the same, the wave heights in very strong storms show a clear decreasing trend near the southern coast. This feature may be responsible for the enhanced coastal erosion in certain areas in the north-east Gulf of Finland (Ryabchuk et al. 2011). It is apparently related to the above-discussed major changes in the wind direction over the Estonian mainland: the frequency of south-west winds has increased considerably over the last 40 yr (Jaagus 2009; Jaagus and Kull 2011).

6 Discussion

The presented data indicate that substantial changes in several core properties of wave fields such as the average wave intensity (in terms of the annual mean significant wave height), very rough wave conditions (understood as the wave height occurring with a probability of 1–5 %) and wave propagation directions have occurred in certain regions of the Baltic Sea since the middle of the 20th century. Interestingly, there is

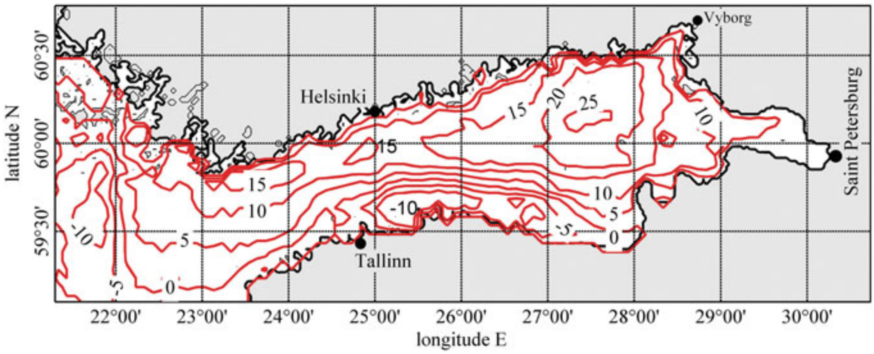

Fig. 11 Spatial distribution of the long-term changes (cm) 99 %-ile of significant wave height in the Gulf of Finland (Soomere and Räämet 2011b)

a very minor change in the spatially averaged wave height and almost no temporal changes in the wave periods. This means that remarkable local changes and associated substantial increase or decrease in the severity of wave-driven hazards may be often overlooked.

An increase in the height of the hindcast extreme waves in the Arkona Basin based on simulations forced by geostrophic winds is not unexpected because the wind speed in this area has grown markedly over the last decades (Pryor and Barthelmie 2003, 2010). A decrease of the same magnitude in the neighbouring sea area to the north-east of Bornholm is counter-intuitive but substantiated well by the abrupt change in the air flow direction over this region (Soomere and Räämet 2014; Soomere et al. 2015).

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 in the northern Baltic Proper. However, no overall increase in the average wave height has occurred in the northern Baltic Proper within the second half of the 20th century. Such a complicated pattern of spatio-temporal changes in various properties of wave fields is not completely unexpected as many studies have shown that the magnitudes of the trends in wave properties can greatly vary in different sea areas (e.g. Weisse and von Storch 2010; Martucci et al. 2010). It is, however, notable that a steep decrease in wave heights may occur in open-sea areas adjacent to those hosting an equally steep increase in wave heights.

Ironically, most of the existing long-term wave observation and measurement sites are located in areas where the simulations have revealed almost no long-term changes in wave properties. The situation is even more complicated because of the mismatch of the long-term behaviour of the mean wave height with the gradual increase in the mean wind speed. A partial explanation is offered by the observation that the wind direction has changed but this highly interesting feature still needs further investigation.

There is now increasing evidence that extreme wave conditions with $H_S \geq 7\,\text{m}$ (first observed in January 1984 in the northern Baltic Sea) occur more or less regularly approximately 1–2 times a decade in both northern and southern parts of the Baltic Proper. It is very likely that the frequency of extreme storms which able to generate such wave conditions has been largely unchanged during the last 30 years. This, however, does not exclude the presence of exceptional events. 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 of the Gulf of Finland, in an area which generally is sheltered from long waves. 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 to the north-north-east), 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 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, and therefore the vertical and horizontal distributions 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 in wind stress at sea surface during relatively windy winter months may lead to further changes in the wave climate, in particular, to enhancing 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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