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Wave Climate and its Decadal Changes in the Baltic Sea Derived from Visual Observations

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

/Inga Zaitseva-Pärnaste/

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EHITUS F42

Läänemere lainekliima ja selle muutlikkus visuaalsete lainevaatluste alusel

INGA ZAITSEVA-PÄRNASTE

TTÜ KIRJASTUS

“THERE’S NO SECRET TO BALANCE.
YOU JUST HAVE TO FEEL THE WAVES.”

Frank Herbert
Chapterhouse: Dune

Contents

List of publications constituting the thesis

The thesis is based on six publications in international peer-reviewed journals. The publications are referred to in the text as Paper I, Paper II, Paper III, Paper IV, Paper V and Paper VI. Papers II–VI are indexed by the ISI Web of Science:

Paper I Soomere T., **Zaitseva I**. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi, *Proceedings of the Estonian Academy of Sciences. Engineering*, **13** (1), 48–64.

Paper II **Zaitseva-Pärnaste I**., Suursaar Ü., Kullas T., Lapimaa S., Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea, *Journal of Coastal Research*, Special Issue **56**, 277–281.

Paper III Räämet A., Soomere T., **Zaitseva-Pärnaste I**. 2010. Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. *Proceedings of the Estonian Academy of Sciences*, **59** (2), 182–192.

Paper IV Soomere T., **Zaitseva-Pärnaste I**., Räämet A. 2011. Variations in wave conditions in Estonian coastal waters from 1 weekly to decadal scales. *Boreal Environment Research*, **16** (Suppl. A), 175–190.

Paper V **Zaitseva-Pärnaste I**., Soomere T., Tribštok O. 2011. Spatial variations in the wave climate change in the eastern part of the Baltic Sea. *Journal of Coastal Research*, Special Issue **64**, 195–199.

Paper VI **Zaitseva-Pärnaste I**., Soomere T. 2013. Interannual variations of ice cover and wave energy flux in the northeastern Baltic Sea. *Annals of Glaciology*, **54** (62), 175–182.

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Introduction

Wind waves impacting the offshore and coasts of the Baltic Sea

Wind waves are probably the most widely known phenomenon of wave nature and the most easily observable property in the sea. This, however, does not mean that the wave phenomena are simple or can be easily described. While a low, smooth, very regular remote swell is largely similar to the classical sinusoidal wave train, wave fields usually constitute an extremely complicated superposition of various components, with different heights, lengths or periods, propagation directions and persistency. Each component should be characterized separately using several parameters, which makes studies into wave phenomena intrinsically complicated (Komen et al., 1994).

Since the sea surface is an almost perfect environment for the propagation long waves and an almost flawless waveguide for windseas as well, surface waves not only endanger vessels and offshore installations but also carry most of their energy to the coast. This feature may become a blessing in terms of wave energy (Cruz, 2008) but also a source of high costs when waves damage a coastal engineering structure, erode a vulnerable coastal section or fill a major fairway with sediments (Dean and Dalrymple, 2002). Waves approaching the coast are often responsible for a number of processes, from sediment transport that gradually reshapes the coastal environment through accumulation, transit and erosion up to various extreme marine-induced coastal hazards and disasters such as flooding or devastating tsunamis. Thus a widespread competence in wave matters is an invaluable asset for all coastal nations, without which, for example, integrated and sustainable management of the coastal zone or safety of shipping and users of the coast is virtually impossible to achieve. As surface waves are also a major driver of many processes in the offshore, studies into their properties and into the wave climate form one of the key elements of contemporary physical oceanography (Leppäranta and Myrberg, 2009; Weisse and von Storch, 2010).

Here, the wave climate is understood in terms of the basic long-term wave properties (average and extreme height, occurrence distributions and height-period combinations) and their spatial variations (Weisse and von Storch, 2010). A comprehensive picture of both the existing wave climate (that is, of the typical and extreme wave properties and their distributions) and its changes in the recent past is of great value for many research areas and engineering applications. In particular, possible increase in the frequency and/or severity of marine coastal hazards along with global climate changes or even a change in the typical wave approach direction may considerably alter the conditions of operation and maintenance of the coastal infrastructure and environment.

The complexity of physics and dynamics of the Baltic Sea (Figure 1) extends far beyond the typical features of many other water bodies of comparable size (Wulff et al., 2001; BACC, 2008). The Baltic Sea is characterized by extremely complex geometry, highly varying wind fields, extensive archipelago areas with specific wave propagation properties and ice cover during a large part of the year. This gives rise *inter alia* to specific wave generation conditions for offshore winds over an irregular coastline (Kahma, 1981; Kahma and Calkoen, 1992; Tuomi et al., 2012) or under so-called slanting fetch frequently occurring in some sub-basins (Pettersson et al., 2010). Changes in the wave climate even in terms of shifts of the stormy season to months with no ice cover may lead to severe destruction of vulnerable beaches (Orviku et al., 2003; Ryabchuk et al., 2010).

The fetch length is quite limited in the Baltic and favourable conditions for the excitation of severe waves occur relatively seldom. The wave climate is relatively mild. This sea at times hosts extremely rough wave conditions with the offshore significant wave height exceeding 9.5 m (Schmager et al., 2008; Soomere et al., 2008a; Tuomi et al., 2011). Storm waves in this water body are relatively steep and short, and thus comparatively dangerous for vessels. In this sense the relatively low levels of wave energy compared to the open ocean (e.g., Bernhoff et al., 2006) may be deceptive. The consequences of wave-induced damage have been most serious in the Baltic Sea. For example, 852 lives were lost when storm waves damaged the passenger ferry *Estonia* in autumn 1994 (Karppinen and Ling, 1998).

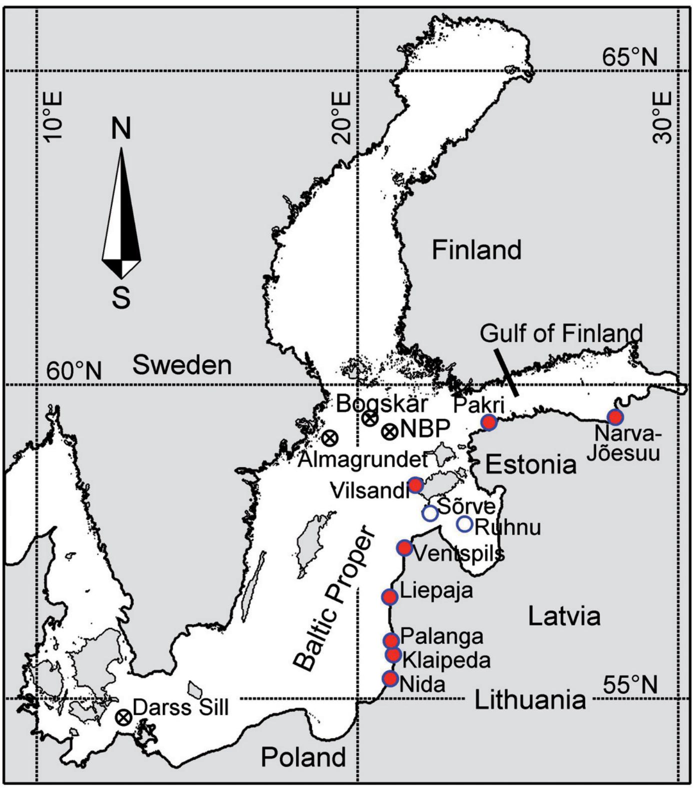

Figure 1. Location scheme of the Baltic Sea, showing the sites of instrumental measurements (crossed circles) and visual wave observation sites at its eastern coast (red circles) and in the Gulf of Riga (white circles).

The properties of the wave climate may be obtained from different sources. A straightforward way is to deploy a sufficient number of contemporary directional wave measurement devices for a sufficiently long time. In general, this is not a viable option, first of all because of the high cost and difficulties in organizing field experiments. More importantly, it is not possible to obtain data retrospectively. Moreover, especially in the context of the Baltic Sea measurements of wave properties at a few sites along a highly variable coastline frequently do not contain enough information about variability of wave fields.

Another, more feasible way is to extract necessary wave statistics from numerically replicated wave fields. This approach has become feasible only recently when the performance of wave models and the quality of numerically replicated open sea wind information have reached the necessary level for reliable reconstruction of wave time series.

A third option is to employ visually observed wave data. Historically, this has been the only way to at least qualitatively quantify and properly display wave properties. The sets of visually observed data have several obvious shortcomings such as the intrinsically present subjectivity, a poor spatial and temporal resolution and highly variable coverage. While observations from ships have been extensively used to identify global changes in wave fields (Gulev and Hasse, 1998, 1999; Gulev and Grigorieva, 2006), observations from the coast have additional issues related to irreversible changes in the wave properties in the nearshore. In particular, owing to the extremely complex geometry and bathymetry of the Baltic Sea, it is often almost impossible to reconstruct the offshore wave properties from those observed near the coast. It is, however, possible to identify *changes* in wave properties at different sites and in this way to recognize the changes in wave generation conditions and to some extent spatial variations in these changes.

A unique feature of many sets of visually observed data from the eastern Baltic Sea is their extremely long coverage. The observations of metric wave height started in the mid-1950s, whereas the data reflecting qualitative appearance of the wave fields goes back as long as to 1946 in many locations (Soomere, 2013). The main focus of this thesis is the analysis of the potential of these unique data sets for the identification of the basic features of wave parameters and for the quantification of their seasonal cycle, interannual variations and long-term changes.

Wave measurements in the Baltic Sea

In spite of the increasing quality of wave models and wind information there is always a need for the validation of the models with *in situ* observed or measured data. Wave measurements are one of the most complicated tasks in physical oceanography. Wave motion and especially wave breaking in the nearshore are accompanied by enormous forces acting on the contact measurement devices. Another reason is the complexity of wave motion. Ideally, the wave measurement device should be able to capture the full wave spectrum, equivalently, a large number of quantities characterizing wave components with different heights, periods and propagation directions that together form a natural wave field.

The problem is particularly complicated in seasonally ice-covered seas where the measurement devices either should be mounted deep enough (e.g., upward-looking echosounders at Almagrundet, Broman et al., 2006) or removed well before the ice season starts (Kahma et al., 2003; Tuomi et al., 2011). This leads to major gaps in the records. As the windiest months in the Baltic Sea are the ones just before the ice season, it is likely that the severest wave conditions may be missing from such records. An accompanying problem is that several commonly used measures of the wave climate become almost meaningless for seasonally ice-covered basins (Tuomi et al., 2011).

Several semi-autonomous wave measurement devices were deployed in the shallow areas of the northern Baltic Sea about three decades ago (Mårtensson and Bergdahl, 1987). A data set recorded in 1978–2003 near the lighthouse of Almagrundet (the western sector of the northern Baltic Proper, 59°09′ N, 19°08′ E, Figure 1) has been analysed in Broman et al. (2006). The data from the years 1978–1993 were found to be most reliable. Later recordings at the turn of the century showed a quite irregular behaviour of wave properties and were only partially analysed. This time period is too short for the reliable description of the local wave climate. Also, the observation site is sheltered from part of the dominating winds.

Contemporary wave recorders have been used in the northern Baltic Sea during a few decades (Pettersson, 1994; Kahma et al., 2003). High-quality wave data sets are available for the sea areas around Finland since the 1970s (Kahma et al., 1983; Kahma and Pettersson, 1993, 1994; Pettersson, 1994, 2001, 2004; Kahma et al., 2003). The wave climate of these areas is fairly well understood (Soomere, 2008). Regular wave measurements using directional waveriders were started in the southern Baltic Sea near the Darss Sill in 1990 (Soomere et al., 2012) and in the central area of the northern Baltic Proper (Figure 1) in September 1996 (Kahma et al., 2003). These data are particularly important for understanding the Baltic Sea wave climate; however, all these time series are much shorter than 30 years, the interval recommended by the World Meteorological Organization for determining the climatological values of the environmental data (WMO, 2001).

The information about wave properties is particularly fragmentary for the eastern part of the Baltic Proper (Soomere et al., 2008a). Hardly any instrumentally measured wave data were available until about 2010 from the coastal areas of Estonia, Latvia and Lithuania except for sporadic measurements made with pressure-based sensors (Soomere, 2005; Laanearu et al., 2007; Soomere et al., 2008a) and bottom-mounted Acoustic Doppler Current Profilers ADCPs (Suursaar et al., 2008). As a result, older sources (e.g., Rzheplinsky, 1965; Davidan et al., 1985) were at times still used for estimates of wave conditions in the eastern part of the Baltic Sea. The only exception is the middle part of the Gulf of Finland where waverider measurements have been performed since the turn of the millennium (Pettersson and Boman, 2002). This area is characterized by extremely complex geometry and thus extensive refraction and diffraction of wave fields. These phenomena may lead not only to large gradients in wave fields (Soomere, 2005; Laanearu et al., 2007) but also to the formation of areas of unusually large concentration of wave energy.

Modelling the Baltic Sea waves and wave climate

The Baltic Sea is a practically closed system of surface waves because very little wave energy may penetrate into it through the Danish straits. Its wave fields are nevertheless very complicated, first of all highly intermittent, that is, temporally and spatially highly variable. As the fetch length is relatively small, both the reaction and decay times of wave fields are comparatively small (Soomere, 2005). The duration of severe wave storms is usually below 8 h (Broman et al., 2006). These features strongly complicate the analysis of the Baltic Sea wave climate as relatively high density of wave measurement or observation sites and/or high resolution of the wave models are necessary to properly resolve rapidly changing wave fields.

The situation is additionally complicated by the anisotropy of the Baltic Sea wind fields. In a large part of the Baltic Proper the predominant winds blow from two directions (south-west and north-north-west, Soomere and Keevallik, 2001). This feature gives rise not only to two-peaked distributions of wave propagation directions but also to the highly anisotropic nature of the Baltic Sea wave fields (Soomere, 2003; Jönsson et al., 2002, 2005). In particular, the presence of predominantly westerly winds suggests that the fetch length and, consequently, wave heights and periods are the largest in the eastern part of the Baltic Sea. This property was recently confirmed by Schmager et al. (2008) and in the efforts towards numerical reconstruction of the wind wave climate in the Baltic Sea (Räämet, 2010; Soomere and Räämet, 2011) performed simultaneously with preparation of this thesis.

Recognition of wave climate changes, in particular, changes in extremes, presumes a thorough knowledge of typical and extreme wave conditions. Several efforts have been made to numerically reconstruct the global wave data set that would suit for the detection of the basic features of the wave climate and their changes in the open ocean conditions. These efforts have led, for example, to the compilation of the KNMI/ERA-40 Wave Atlas (Sterl and Caires, 2005). The atlas is based on an atmospheric reanalysis data set covering the period from September 1957 to August 2002 by the European Centre for Medium Range Weather Forecasts and represents 6-hourly means of wave properties over an average of $1.5°\times1.5°$ areas. Such products provide reliable wave climatology for open ocean conditions but their resolution is too coarse for the Baltic Sea conditions.

Complicated geometry of the Baltic Sea and the lack of reliable wind data make an adequate reproduction of wave properties of this basin a major challenge (Räämet et al., 2009). For selected locations the wave climate can be reconstructed and its changes detected on the basis of simple (for example, fetch-based) models using standard one-point wind information (Suursaar et al., 2008; Suursaar and Kullas, 2009a, 2009b; Suursaar, 2010, 2013). This approach can be realized for semi-sheltered sea areas with a short memory of wave fields such as the middle and eastern parts of the Gulf of Finland (Soomere, 2005; Laanearu et al., 2007). It is, however, usually not applicable to the entire Baltic Sea, the wind and wave fields of which exhibit extensive spatial variability.

A possible solution is a high-resolution numerical reconstruction of the wave climate for the entire Baltic Sea based on either measured or modelled wind information. Since the waves from the rest of the World Ocean practically do not affect the Baltic Sea waves, the wave properties here can be modelled with the use of local models. Earlier numerical wave studies in the Baltic Sea basin have been discussed in detail in Broman et al. (2006) and Soomere (2008). Their central conclusion is that the spatial distribution of wave activity reflects the anisotropy of the wind regime in the Baltic Proper (Mietus, 1998; Soomere, 2003). Statistically, the regions of the largest wave activity are found along the eastern coasts of the Baltic Proper (Jönsson et al., 2002, 2005). A number of studies have been performed for limited areas of the Baltic Sea (Gayer et al., 1995; Paplińska, 1999, 2001; Blomgren et al., 2001; Cieslikiewicz and Herman, 2002). Several other simulations (Cieslikiewicz and Paplinska-Swerpel, 2008; Kriezi and Broman, 2008) are reported in the literature but no details of the wave regime are presented.

The critical factor in wave modelling is the quality of available wind information. Some authors have used wind information from coastal measurement sites (Blomgren et al., 2001). These sites do not necessarily represent the actual properties of marine winds, especially in the areas of complicated geometry and large-scale topographic features (Keevallik, 2003a). The common experience so far is that none of the existing numerical replications of the wind fields is perfectly suited for wave simulations and that the reliability of the national wind data bases (such as the MESAN, operational Mesoscale Analysis System, Swedish Meteorological and Hydrological Institute (SMHI); hourly gridded wind information on a 22 km grid since October 1996, Häggmark et al., 2000) considerably decreases with the distance from the national coast (Räämet et al., 2009). For this reason, simple derivatives of the geostrophic winds have frequently been used to substitute the true marine winds in wave and current modelling (Myrberg et al., 2010; Räämet, 2010; Lehmann et al., 2013).

An adequate wave climatology based on long-term simulations of the Baltic Sea wave fields was still missing when work on this thesis started. Only several fragments of simulations by J. Augustin and R. Weisse (Augustin, 2005) were reflected in Schmager et al. (2008) and in BACC (2008). The first long-term simulation was successfully performed in 2009–2011 in parallel with the present work. Recent efforts towards the numerical replication of the wave climate are described in detail in the PhD thesis by Räämet (2010) and presented in several overviews (see Soomere and Räämet, 2011 for detailed bibliography).

Changing wave climate of the Baltic Sea

It is well known that in many situations the wave height increases as the wind speed squared (e.g., Dean and Dalrymple, 1991). The wave energy flux (that drives the evolution of coasts) is proportional to the wave height to the power of 2.5 at the breaker line (USACE, 2002) and thus reflects sometimes the wind speed to the power of 5. These features explain why the characteristics of waves (more generally, wave climate) and especially wave-driven coastal processes are one of the most sensitive and robust indicators of changes in the wind regime and local climate (Weisse and von Storch, 2010).

Large changes in the wave climate are unlikely on the open ocean coasts where a great part of wave energy arrives in the form of swell waves (Dodet et al., 2010; Dragani et al., 2010). On the contrary, even small changes in the wind regime may easily lead to large variations in wave properties and extensive consequences for sedimentary beaches developing in fetch-limited conditions of semi-enclosed basins. This is also reflected in estimates of the potential increase in wave heights. For example, potential climate changes in the North Sea may host a considerable (18%) increase in the 99%-iles of the (largest) wave heights while for the wind speed a similar increase is 7% (Grabemann and Weisse, 2008).

Several other features of climate variations can strongly affect the properties of the Baltic Sea waves. The irregular shape of the Baltic Sea may considerably alter the wave properties if the wind direction changes. A change in the predominant wind direction may lead to a substantial increase in the typical fetch length in such basins. Such a change would evidently also result in numerous alterations in the reaction of water masses of the sea, from changes in the pattern of upwelling and downwelling areas (Lehmann and Myrberg, 2008) to a considerable change in the probability of occurrence of high water levels (Johansson et al., 2001). Quite large changes will evidently occur in the typical and extreme wave conditions, especially in the wave approach directions, with possibly severe consequences to the evolution of sedimentary coasts (Viška and Soomere, 2012). Such changes may have taken place in the recent past. Namely, a drastic increase in the frequency of south-western winds over the latter half-century (Kull, 2005; Jaagus, 2009) may have resulted in a combination of an increase in wave periods and a change in the wave propagation direction.

Equally important changes in wave fields and the reaction of the coast may stem from potential alterations in ice cover. Sea ice is one of the decisive factors of wave activity and, more importantly, coastal processes in seasonally ice-covered seas. From the viewpoint of available wave energy it first reshapes the area of wave generation (fetch length), thereby affecting waves even far downwind from the ice region. It also affects back atmospheric conditions so that the wind speed over a frozen sea may be larger than over rough wind-generated seas (Leppäranta, 2012). More importantly, it protects sedimentary coasts from the direct impact of waves, thereby reducing the overall intensity of coastal processes (Orviku et al., 2003; Ryabchuk et al., 2011).

Extensive relatively shallow areas in the Baltic may host unexpectedly high waves, formed in the process of wave refraction and wave energy concentration in some areas (Soomere, 2003, 2005; Soomere et al., 2008a). Changes in the wave approach direction or in wave periods may essentially modify the existing refraction pattern and shift the location of major wave-driven damage.

The temporal coverage of wave climate studies is usually limited by the length of the existing wave time series. As most of the available time series are fairly short and come from a few points only, it is not surprising that the evidence of changes in some properties of wave fields was controversial when this work was started. Moreover, the data largely came from implicit sources such as the rate of coastal erosion (Orviku et al., 2003). The available information suggested that the changes in the Baltic Sea wave climate were marginal from the late 1950s until the early 1990s (WASA Group, 1995, 1998; Mietus and von Storch, 1997). According to instrumental measurements from Almagrundet, the wave heights apparently increased in the northern Baltic Proper from the end of the 1970s and until the middle of the 1990s at Vilsandi (Broman et al., 2006).

This course was consistent with the common understanding that the storminess in the Baltic Sea region was relatively modest in the middle of the 20th century and increased to some extent by the end of the millennium (Alexandersson et al., 1998). This finding also matched the gradual increase in the wind speed in the northern Baltic Proper (the island of Utö, Broman et al., 2006). A rapid decrease in the annual mean wave heights in this area in the mid-1990s, revealed by another data set (Broman et al., 2006), was thus highly controversial (Soomere, 2008). Moreover, wave heights along the Lithuanian coast showed even a decrease over the 1990s (Kelpšaite et al., 2008), whereas no change was reported for Tallinn Bay (Kelpšaite et al., 2009).

The above mismatch of the decadal variability in the wave heights and wind speed over the northern Baltic Proper was one of the major motivations for the work presented in this thesis. In such cases the ground truth about actual changes in wave properties may provide a clue to what has really happened with the wave generation or propagation conditions. Numerous changes in the forcing conditions and in the reaction of the water masses of the Baltic Sea have been reported during the last decades (BACC, 2008). There is evidence that the increasing storminess in this region which started in the 1970s caused extensive erosion of the depositional coasts (Orviku et al., 2003; Eberhards et al., 2006; Tõnisson et al., 2008; Ryabchuk et al., 2009, 2011). This trend, however, has been strongly questioned by many authors. The intensity and duration of severe wave storms in the southern North Sea have decreased since about 1990–1995 (Weisse and Günther, 2007) consistently with the updated trends of storminess (Alexandersson et al., 2000).

Very rough seas measured twice in the Baltic Proper in December 1999 (Kahma et al., 2003) and two ferocious winter storms in 2004/2005 (Suursaar et al. 2006; Soomere et al. 2008a; Tuomi et al., 2011) reinforced the discussion as to whether the wave conditions in the Baltic Sea have become rougher than a few decades ago. One exceptional storm, Gudrun in January 2005, highlighted inadequate awareness of extreme wave properties (Soomere et al., 2008a) and of the height and spatial extent of extreme water levels (Suursaar et al., 2006). The all-time highest significant wave height (8.2 m) was recorded in December 2004, just a few weeks before this storm (Tuomi et al., 2011). The all-time highest waves were measured in the Gulf of Finland in November 2001 (Pettersson and Boman, 2002; Soomere, 2005).

Objective and outline of the thesis

The evidence presented above raised a number of questions concerning the properties of and possible changes in the Baltic Sea wave climate. Many of the described changes, if they happen to be real, can largely affect the safety of offshore operations (Bitner-Gregersen et al., 2013), thus, lives and property of people. Another direct consequence is potential intensification of coastal processes, with expensive implications in terms of the extra costs of the construction and maintenance of various coastal engineering structures, more frequent dredging, etc. In essence, the presented circumstances highlighted the necessity for a re-evaluation of the basic features of the Baltic Sea wave climate based on the physical evidence about actual wave fields. This challenge also included the need for a quantification of the potential variability of wave properties along the coasts of this basin.

The main objective of this thesis is to reconstruct the wind wave climate and its possible long-term and decadal variations for the eastern Baltic Proper and the Gulf of Finland, with a focus on the coastal waters of Estonia, by using the historical visual observations of wave properties. Although a single observation may contain considerable uncertainties, the use of a large number of uncorrelated measurements is generally a consistent way to feasibly reconstruct the past wave activity (Gulev and Hasse, 1998, 1999). As will be discussed below, this method has potential for providing reliable wave statistics in the nearshore. Although the observed wave properties are site-specific, the resulting data sets make it possible to identify several large-scale temporal and spatial variations in the wave fields. As these data characterize the eastern (downwind) parts of the Baltic Sea, they form a valuable basis for the identification of changes in the climate of the entire Baltic Sea basin.

Last but not least, the extracted information serves as an invaluable source of ground truth for verifying the performance of the Baltic Sea wave models and an important input for the validation of climate models. A comprehensive comparison of these data sets with the results of simulations has great potential for clarifying whether the above-described mismatches stem from the uncertainties of wave models and measurements, represent properties of local wave fields or form a part of long-term changes. The available set of instrumentally measured wave data is fairly small in this area and of little use for resolving these issues. It is not always possible to reconstruct the open sea wave properties from the results of nearshore observations but changes in wave generation conditions can eventually be recognized from these data.

The particular objectives of the thesis are as follows:

- to reconstruct the basic features of the nearshore wave climate of the Baltic Sea and in the Gulf of Finland from historical visual observations back to the middle of the 20th century;
- to identify and quantify the core changes and trends in the main properties of waves in different regions in the eastern Baltic Sea;
- to identify spatial variability of the wave climate in this region, especially concerning the wave height;
- to establish the magnitude of decadal variability in the wave properties in the eastern Baltic Sea.

As mentioned above, a large part of the work described in this thesis was performed in parallel with a high-resolution numerical reconstruction of the Baltic Sea wave fields using the wave model WAM and adjusted geostrophic wind fields (Räämet, 2010). The cooperation resulted in joint publications (Papers III and IV) in which the ground truth extracted from visual observations was used to verify and validate the modelled results. The wave fields modelled in Räämet (2010) were later used to analyse the interrelations of ice cover and wave fields in Paper VI. This feature naturally leads to some overlap of part of the technical material (description of the existing properties of the wave climate, the wave observation sites, data sets and the wave model) in this thesis and in Räämet (2010).

The analysis below involves wave heights specified in various manners: visually observed wave heights, the significant wave height calculated based on Rayleigh statistics at Almagrundet and the significant wave height calculated using two models (a fetch-based model and a full spectral wave model WAM). On the one hand, the potential differences between these quantities, for example, because of violation of the Rayleigh distribution in the nearshore, suggest that both the instantaneous and average values of some characteristics found on the basis of different sources may differ to some extent. On the other hand, the use of a particular method for retrieving the wave height apparently does not distort the basic features of spatio-temporal variations in the wave fields such as their typical time scales and the sign and relative magnitudes of the trends.

Chapter 1 gives a short insight into recent wave climate studies performed for the North Atlantic and the North Sea. As the majority of low pressure systems that excite rough waves in the Baltic Sea stem from the North Atlantic, changes in the storm pattern in this area are evidently reflected in the wave conditions in the North Sea and the Baltic Sea. The rest of this chapter addresses the wave climate studies in the Baltic Sea and the data sources for these studies.

Chapter 2 starts with a short overview of the specific features of processing and analysis of the visually observed wave data. As I make an attempt to merge the results of this analysis with the output of numerical hindcasts and existing long-term measured wave data, I give a short description of the wave model the output of which is used in comparisons. The main goal of the chapter is to delineate the main features of the Baltic Sea wave climate, with emphasis on the eastern Baltic Sea.

Chapter 3 presents a selection of results of the observed decadal and long-term changes in the wave climate of the eastern Baltic Sea and a comparison of these changes with similar variations in the instrumentally measured and hindcast data. The emphasis is on the annual mean wave height and most frequent wave approach direction. Finally, I address several questions of interrelations between certain average parameters of observed wave conditions and the ice phenomena, with the goal of specifying quantities suitable for characterizing the wave loads in seasonally ice-covered seas.

Approbation of the results

The main results have been presented at the following international conferences:

1. Zaitseva I., Soomere T. 2008. On long-term variations of the wave conditions in the Northern Baltic Sea. Oral presentation at the *US-EU-Baltic 2008 International Symposium* (27–29 May 2008, Tallinn, Estonia).
2. Zaitseva-Pärnaste I., 2008. Long-term variations of wave conditions in the northern Baltic Sea derived from visual observations from Vilsandi, Pakri and Narva-Jõesuu. Poster presentation at the *3rd International Student Conference "Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region"* (9–12 October 2008, Klaipėda, Lithuania).
3. Zaitseva I., Kelpšaite L. 2008. Wave regime changes at the Baltic Sea Eastern coast. Oral presentation at the *SEAMOCS Network Meeting and Conference* (22–25 October 2008, Oslo, Norway).
4. Zaitseva-Pärnaste I., Suursaar Ü., Kullas T., Lapimaa S., Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. Oral presentation at the *10th International Coastal Symposium* (13–18 April 2009, Lisbon, Portugal).
5. Zaitseva I., Suursaar Ü., Soomere T. 2009. Seasonal and long-term variations of wave conditions in Estonian coastal waters. Oral presentation at the *7th Baltic Sea Science Congress* (17–21 August 2009, Tallinn, Estonia).
6. Zaitseva I., Soomere T. 2009. Long term variation in wave fields in the Baltic Proper. Oral presentation at the *SEAMOCS Closure Meeting* (8–10 September 2009, Toulouse, France).
7. Zaitseva-Pärnaste I., Soomere T. 2009. Long term variation in wave fields in the Baltic Proper. Poster presentation at the *International Conference on Lithodynamics of Bottom Contact Zone of the Ocean* (14–17 September 2009, Moscow, Russia).
8. Zaitseva-Pärnaste I., Soomere T. 2009. Seasonal and long-term variations of wave conditions in Estonian coastal waters. Oral presentation at the

International Conference on Complexity of Nonlinear Waves (5–7 October 2009, Tallinn, Estonia).

9. Zaitseva-Pärnaste I., Räämet A., Soomere T. 2010. Comparison between modelled and measured wind wave parameters in Estonian coastal waters. Poster presentation at the *2nd International Conference on the Dynamics of Coastal Zone of Non-Tidal Seas* (27–30 June 2010, Baltiysk, Kaliningrad Oblast, Russia).
10. Zaitseva-Pärnaste I., Soomere T. 2010. Long-term variation of wave heights and its comparison with ice conditions in Estonian coastal waters. Oral presentation at the *10th International Marine Geological Conference "The Baltic Sea Geology – 10"* (24–28 August 2010, Saint Petersburg, Russia).
11. Zaitseva-Pärnaste I., Soomere T. 2010. Wave climate in the eastern part of the Baltic Sea. Poster presentation at the *5th International Student Conference on Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region* (6–8 October 2010, Palanga, Lithuania).
12. Zaitseva-Pärnaste I., Soomere T. 2012. Interannual variations of ice cover and wave energy flux in the north-eastern Baltic Sea. Poster presentation at the *International Symposium on "Seasonal Snow and Ice"* (28 May–01 June 2012, Lahti, Finland).

1. Wave climate studies in the Baltic Sea and adjacent areas

Wave conditions in the interior of the Baltic Sea are almost independent of the wave properties in the North Atlantic and the North Sea as virtually no wind wave energy penetrates from the Skagerrak to the Baltic Proper. Wave properties in these basins are still implicitly interrelated because the majority of weather systems affecting the Baltic Sea wave fields stem from the North Atlantic. Many of these weather systems also touch the North Sea on their way to the Baltic. Therefore, the changes in the wave properties in the North Sea and partially even in the North Atlantic eventually mirror similar changes in the Baltic Sea. Moreover, these areas have played a particular role in the development of contemporary perception of wave dynamics, for example, through the introduction of the concept of saturated wave systems or the progress in understanding the properties of fetch-limited wave growth (Komen et al., 1994).

As a comprehensive overview of the research into changes in the wave climate in the North Atlantic and the North Sea is available in a recent PhD thesis (Räämet, 2010), I only discuss the main features of these changes that have clear relevance to the results and main conclusions presented below. Next I describe the outcome of the recent Baltic Sea wave climate studies and the core source of information used in this thesis – the history, setup and routine of visual wave observations in the Baltic Sea.

1.1. Changes in the wave climate in the North Atlantic and the North Sea

Many authors have expressed the opinion that the North Atlantic probably hosts the world's roughest wave climate in terms of the highest waves occurring once in a longer time interval (Caires and Sterl, 2005; Grigorieva and Gulev, 2006). Strong winds and high waves are created in this region by the interplay of the frequent generation of strong cyclones and the presence of high orography in Greenland, Iceland and Scandinavia. The highest ever instrumentally measured offshore significant wave height $H_S = 18.5$ m has been registered at Rockall, west of Scotland (Holliday et al., 2006). The second highest offshore significant wave height, 17.9 m, has been measured in the Gulf of Mexico (Wang et al., 2005). These records have only been exceeded in an area with complicated bathymetry near Taiwan under typhoon Krosa where the significant wave height reached 24 m (Babanin et al., 2011) and the highest single wave 32.3 m (Liu et al., 2008).

The combination of the frequently occurring high waves and extremely intense ship traffic has initiated a number of studies into properties of the wave climate and its changes over the last 100 years in the North Atlantic. Early analyses exhibited controversial results, because relatively limited time intervals and selected sea areas were addressed. For example, Bacon and Carter (1991) found an increasing trend (about 2%/year) in the mean wave heights in the entire North Atlantic since 1950. The international Waves and Storms in the North Atlantic (WASA) project (WASA Group, 1998) concluded that the wave climate in the north-east Atlantic and in the North Sea had exerted significant decadal variations but revealed no clear trends. Thus, the average wave intensity at the end of the 1990s was comparable with that at the beginning of the 20th century.

Further numerical reanalyses of wave properties increased both the resolution and temporal coverage of the data sets. The first numerically reconstructed global wave data set using realistic wind fields and contemporary wave models was compiled in the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR). The reanalysis project attempted to produce a temporally homogeneous data set over the 40-year period 1957–1996 (Kalnay et al., 1996). Using these wind data, Swail et al. (1998, 2000) detected a significant increasing trend in wave heights in the north-eastern Atlantic and a decreasing trend in the central North Atlantic. Later it was shown that the NCEP/NCAR reanalysis underestimated the near-surface wind speed (Smith et al., 2001). This feature probably led to an underestimation of wave heights but apparently did not affect the presence or absence of trends in wave properties.

Further research associated the changes in wind and wave properties with particular seasons. Geng and Sugi (2001) identified an increase in cyclonic activity in winter in 1958–1998. This feature was associated with a statistically significant trend in the 90%-iles and 99%-iles of significant wave height for the North Atlantic for the winter (January–March) season. The changes in wave intensity exhibited a clear regional pattern (Wang and Swail, 2002). An extended analysis of the storm climate of the north-east Atlantic for 1958–2001 showed that the average number of storms had increased near the exit of the North Atlantic storm track during that period (Weisse et al., 2005).

Another seminal product was created by the European Centre for Medium-Range Weather Forecasts (ECMWF). The so-called ERA-40 reanalysis project covers 45 years from 1957 to 2002 (Uppala et al., 2005). Using different versions of the ECMWF products, Kushnir et al. (1997) identified an increase in significant wave height at several locations in the North Atlantic since the 1960s. Contrariwise, Sterl et al. (1998) found no significant change in wave heights for another 15-year period. Such discrepancies are not unexpected because the typical time scale of changes in wave parameters is 15–30 years (Vikebø et al., 2003; Soomere, 2008).

The final result of the ERA-40 wave reanalysis is a web-based KNMI/ERA-40 atlas of 6-hourly means of wave properties with a spatial resolution of 1.5°×1.5° (Sterl and Caires, 2005). Using this product, Caires and Sterl (2005) showed that the most extreme wave conditions are likely to occur in the storm track regions and that the globally highest 100-year return values of wave heights are likely to occur in the North Atlantic. The spatial resolution of this database is, however, too coarse for an effective use in the Baltic Sea.

Similarly to the North Atlantic, Bacon and Carter (1991) revealed an increase in mean wave heights in the North Sea from about 1960 to a peak around 1980 and a decrease since then. Still, winters at the end of the 1980s had very severe wave conditions in the northern North Sea. The NCEP/NCAR reanalysis showed an increase in annual mean wind speed of about 10% during 1957–1996, mainly within the period from October to March (Siegismund and Schrum, 2001). Not surprisingly in this context, significant wave heights increased in 1955–1999, mainly in the northern part of the North Sea (Vikebø et al., 2003). Interestingly, a much longer period 1881–1999 did not contain any distinct trend. Instead, a substantial multi-decadal variability was identified, with a decrease in wave heights at the turn of the 19th/20th centuries and a similar gradual increase during the second half of the 20th century.

Further studies have reinforced the perception that considerable interannual variations have taken place in wave intensity and partially over longer time intervals, but no significant changes in the severity of wind or wave conditions, as well in storm surges, have occurred in the North Sea (Weisse et al., 2002, 2005; Weisse and Plüß, 2006). The wave conditions showed high spatial variation (Weisse and Günther, 2007) similarly to the variations identified for the Baltic Sea from visual observations in Papers II and V and numerically in Soomere and Räämet (2013). For example, the annual 99%-ile wave height had increased by up to 1.8 cm/year off the Netherlands, German and Danish coasts, whereas a decrease occurred simultaneously off the British coast. This increase was mainly caused by an increase in the number of extreme events, whereas their duration and intensity revealed no significant changes (Weisse and Günther, 2007).

Visual observations from ships have been extensively used for the production of wave statistics in the past (Hogben and Lumb, 1967; Hogben et al., 1986). Gulev et al. (2003) systematically considered their global match of the data set recorded visually by voluntary observing ships (VOS) against various instrumental records. The visual data adequately represented measured wave heights (both windseas and swells) and had a small systematic bias in the periods (Gulev and Hasse, 1998). A climatological set of main wave parameters for the years 1958–1997 for the entire ocean with a resolution of 2°×2°on the basis of the VOS data is described in Gulev et al. (2003). In the context of the data and approach presented in this thesis, the most interesting are their results about potential biases that are inherent in visual wave data. These biases were identified and partially corrected by using the WAM wave model (Komen et al., 1994). Gulev et al. (2003) observed the highest sampling biases in the South Ocean where (usually under relatively severe conditions) the VOS data considerably (by up to 1–1.5 m) underestimated the wave heights.

Gulev and Hasse (1998) were probably the first to conclude that observations from merchant ships can be effectively used to quantify changes in the wave climate and storminess. Wave climate changes estimated from the VOS data were found to be generally consistent with those shown by the instrumental records (Gulev and Hasse, 1998, 1999). According to the VOS data, the significant wave height increased by 10–30 cm/decade over the entire North Atlantic in 1964–1993, except for some subtropical areas (Gulev and Hasse, 1999). The changes were mostly concentrated in the properties of the swell. This feature apparently reflects a shift of storms to a more southern position. The largest discrepancy was in the north-eastern Atlantic in 1964–1993, for which the VOS data did not show any significant change but Bacon and Carter (1991) reported considerable variations. Gulev and Grigorieva (2006) extended the analysis over the North Atlantic and North Pacific for the years 1958–2002. The results exhibited a strong seasonal signal. The winter significant wave height increased as much as about 10–40 cm per decade. This increase mostly resulted from the increase in the intensity of windseas. As the Baltic Sea wave fields are dominated by windseas, it is natural to expect a similar increase in this basin as demonstrated in Broman et al. (2006).

1.2. Wave climate studies in the Baltic Sea

Studies of the Baltic Sea wave properties extend back for many decades. Their outcome, mostly based on visual wave observations and simplified wave models in the past, is presented in several generations of wave atlases and textbooks (Rzheplinsky, 1965; Rzheplinsky and Brekhovskikh, 1967; Druet et al., 1972; Russian Shipping Registry, 1974; Davidan et al., 1978, 1985; Schmager, 1979; Sparre, 1982). The use of these sources is, however, not straightforward because changes may have occurred in wave fields over decades. A more contemporary perspective to the Baltic Sea wave fields is represented in DWD (2006) and Lopatukhin et al. (2006a, 2006b). As several recent overviews of wave climate studies are available (Soomere, 2008; Räämet, 2010; Soomere and Räämet, 2011) or under review (Hünicke et al., 2013), I only shortly describe here the basic sources of the relevant data sets.

The anisotropy of predominant winds (Mietus, 1998; Soomere and Keevallik, 2001) suggests that the highest and longest waves occur either at the entrance to the Gulf of Finland, off the coasts of Saaremaa, Hiiumaa and Latvia, or along the Polish coasts (Augustin, 2005; Schmager et al., 2008). Wave data from the northern part of the Baltic Proper thus adequately represent both the average and the roughest wave situations in a large part of the region.

Contemporary wave measurements were launched in the northern Baltic Sea at the end of the 1970s. They were performed in 1978–2003 near the lighthouse of Almagrundet (59°09′ N, 19°08′ E, Figure 1) at a depth of about 30 m and for a short time near Hoburg, south of Gotland (Mårtensson and Bergdahl, 1987). Single waves were identified from the record of the position of the water surface with the zero-downcrossing method (IAHR, 1989). An estimate of the significant wave height H_S was found from the 10th highest wave over 640 s long sections of the record under the assumption that wave heights are Rayleigh distributed. Wave components with periods of less than 1.5 s were removed.

The data from Almagrundet (Broman et al., 2006) are today the longest instrumentally measured wave data set in the Baltic Sea. The set of 95 458 measurements from 1978–1995 reliably describes the wave properties. Later 46 671 recordings, taken in 1993–2003 with another device, have certain quality problems: the overall behaviour of the wave height follows the sea state, but the periods are not usable (Broman et al., 2006). The location is sheltered from part of the dominating winds (the fetch for winds from the south-west, west, and north-west is quite limited at this site) and therefore the data may not fully represent the open-sea wave conditions (Kahma et al., 2003). Several unique wave data sets measured in sea areas surrounding Finland (including directional wave data from the Sea of Bothnia and the Gulf of Finland over several years; cited here after Soomere, 2005) since the 1980s are available in internal reports (Kahma et al., 1983; Kahma and Pettersson, 1993; Pettersson, 1994) or local report series (Pettersson, 2001; Kahma et al., 2003).

A wave buoy was deployed near Bogskär in 1983–1986 at a site completely open to the sea (59°28.0′ N, 20°21.0′ E, Figure 1). This device estimated the significant wave height as $H_S = 4\sqrt{m_0}$, where m_0 is the total variance of the water surface displacement. The available data (equivalent to about 2 years of uninterrupted measurements) are concentrated in the autumn season and thus represent well the wave climate during relatively windy months (Kahma et al., 2003).

Wave fields in the southern Baltic Sea near the Darss Sill have been measured with a directional waverider since 29 January 1991. The water depth at the site (54°41.9′ N, 12°42.0′ E, Figure 1) is 20 m. The wave parameters are calculated onboard the buoy over 1600 s time series of surface displacement. An analysis of the first 20 years of measurements is presented in Soomere et al. (2011, 2012). This data set represents wave properties in a relatively sheltered region.

A directional waverider has been operated in the northern Baltic Proper at a depth of about 100 m (59°15′ N, 21°00′ E, Figure 1) since September 1996 during ice-free seasons (Kahma et al., 2003; Tuomi et al., 2012). This device also estimates the significant wave height from the water surface displacement. The wave statistics and scatter diagrams for this measurement site (Kahma et al., 2003) as well as selected sections from these data serve as the most reliable information about the main characteristics of the open-sea wave fields in the Baltic (Soomere, 2008). However, to date, this time series is not yet long enough for determining the climatological values of wave properties.

Directional wave measurements were performed in the Gulf of Finland in 1990–1991 and 1994 (Kahma and Pettersson, 1993; Pettersson, 2001), and from November 2001 onwards during ice-free seasons. Only a very limited amount of relevant information has been made available in international publications (Soomere et al., 2008a).

Wave information is particularly fragmentary for the eastern part of the Baltic Proper. Instrumental wave measurements were almost missing for the coastal area of the Baltic States when work on this thesis began (Soomere, 2005; 2008). Only starting from the end of the 2000s, ADCP-based data sets cover several regions and time intervals of considerable length (Suursaar and Kullas, 2009a, 2009b; Paper II, Suursaar, 2010, 2013).

Lack of long-term instrumentally measured wave time series from this area makes all available wave data sets, including the visually observed ones, an important source for wave research. This lack also increases the role and importance of numerical reconstructions of the wave climate for the Baltic Sea. Such efforts have been made since the end of the 1990s using several wave models of various generations, from fetch-based models up to full spectral wave models (Mietus and von Storch, 1997; Tuomi et al., 1999; Soomere, 2001; Jönsson et al., 2003; Augustin, 2005; Alari et al., 2008; Cieslikiewicz and Paplinska-Swerpel, 2008; Kriezi and Broman, 2008; Suursaar and Kullas, 2009a, 2009b). The models used in the first years had relatively low spatial resolution and temporal coverage of simulations. The second generation spectral wave model Hybrid Parametrical Shallow water model (HYPAS, Günther and Rosenthal, 1995) was run with a spatial resolution of 5 nautical miles during a 12-month period in 1999 (Jönsson et al., 2002). The we climate over 19 years (1978–1996) was derived with the use of the wave model WAVAD (Resio, 1993) in the Pomeranian Bay and outside the Polish, Lithuanian and Latvian coasts (Blomgren et al., 2001).

The situation improved considerably within a few years. The results of the modelling of waves using two contemporary models WAM (Komen et al., 1994) and Simulating WAves Nearshore (SWAN) (Booji et al., 1999) during several storms in the years 1998–2001 showed a good agreement (Cieslikiewicz and Herman, 2002). The modelled wave heights were also found to well correspond to satellite observations (Cieslikiewicz and Paplinska-Swerpel, 2008; Tuomi et al., 2011). In recent years several simulations with a resolution of about 3 nautical miles and covering about four decades have been conducted (Augustin, 2005; Cieslikiewicz and Paplinska-Swerpel, 2008; Kriezi and Broman, 2008; Schmager et al., 2008). In particular, results of a run with the WAM model forced by adjusted geostrophic winds have been extensively used to describe spatio-temporal variability of the Baltic Sea wave climate (Räämet et al., 2009; Räämet, 2010; Soomere and Räämet, 2011, 2013).

The common opinion today is that all the contemporary models perform well in the open sea provided the wind information is adequate. Problems in spatial and directional resolution that might occur near the coasts can be resolved by using multi-nested or other types of high-resolution models (Soomere, 2005; Laanearu et al., 2007; Tuomi et al., 2012). A more subtle problem is connected with the presence of a large number of wave fields with very short periods (peak period below 2 s) in semi-sheltered basins of the Baltic Sea (Papers I, II, V; Soomere et al., 2012). It can be solved by extending the frequency range of modelled waves up to about 2 Hz (Soomere, 2005), which also proper handling of the growth of short waves in low wind conditions after calm situations.

The relatively small size of the Baltic Sea, frequent large-scale homogeneity in wind fields and the short saturation time and memory of wave fields make it possible to use simplified wave hindcast schemes (Soomere, 2005) and/or properly calibrated simple fetch-based wave models (Suursaar and Kullas, 2009a, 2009b; Suursaar, 2010, 2013) to reproduce the local wave statistics with an acceptable accuracy. The use of such models for the identification of spatial changes in wave statistics is limited as they basically reproduce the changes in the local wind field only.

The current perception of the Baltic Sea wave climate based on the results of measurements, analysis of visual observations and various hindcasts is presented in several papers (Soomere, 2008; Leppäranta and Myrberg, 2009; Hünicke et al., 2013). Hünicke et al. (2013) also integrate the knowledge developed in this thesis.

The Baltic Sea wave climate is, on average, very mild. The typical long-term significant wave heights are about 1 m in the Baltic Proper (Kahma et al., 2003; Broman et al., 2006; Schmager et al., 2008; Tuomi et al., 2011), 0.6–0.8 m in the open parts of its larger sub-basins such as the Gulf of Finland (Soomere et al., 2010) or Arkona Basin (Soomere et al., 2012), and well below 0.5 m in semi-sheltered bays such as Tallinn Bay (Soomere, 2005; Kelpšaite et al., 2009). These values are by 10–20% lower in the nearshore regions (Suursaar and Kullas, 2009a, 2009b; Suursaar, 2010). The most frequent wave heights are also about 20% lower than the long-term average wave height (Kahma et al., 2003; Soomere, 2008; Soomere et al., 2012). The spatial pattern of average wave heights apparently contains either an elongated maximum (Augustin, 2005; Tuomi et al., 2011) or several local maxima in the eastern Baltic Proper (Jönsson et al., 2003). A hindcast using geostrophic winds indicates another possible maximum to the south of Gotland (Räämet and Soomere, 2010). A very similar spatial pattern exists for the heights of extreme waves (the threshold for the 1%, or equivalently, the 99%-ile of significant wave height for each year) (Soomere and Räämet, 2011).

The Baltic Sea wave climate is highly intermittent. The sea at times hosts very severe wave storms. The largest instrumentally measured significant wave heights are 8.2 m in the northern Baltic Proper on 22 December 2004 (Tuomi et al., 2011) and 7.82 m on 13/14 January 1984 at Almagrundet (an alternative estimate from the wave spectrum is 7.28 m; Broman et al., 2006). The highest individual waves were 14 and 12.75 m, respectively. Numerical simulations indicate 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 and to the north-west of the Latvian coast (Soomere et al., 2008a; Tuomi et al., 2011) and also in the south-eastern part of the sea (Schmager et al., 2008). The extreme wave heights are much lower in sub-basins of the Baltic Sea. On 15 November 2001 the all-time highest significant wave height (5.2 m) was measured in the central part of the Gulf of Finland (Pettersson and Boman, 2002; Soomere et al., 2008b). This wave height was recorded once more in November 2012.

The most frequent wave periods are 3–5 s in the offshore and 2–4 s in the coastal areas (Papers I, II, V; Soomere, 2008). The majority of the combinations of wave heights and periods roughly correspond to the wave fields with a Pierson-Moskowitz (PM) spectrum (Soomere, 2008; Räämet et al., 2010; Soomere et al., 2012). The properties of the roughest seas, however, match better a Joint North Sea

Wave Project (JONSWAP) spectrum (corresponding to fetch-limited seas and characterized by shorter periods than wave fields with a PM spectrum), especially in areas with limited fetch such as the Darss Sill (Soomere et al., 2012). The proportion of swells is very limited in all parts of the Baltic.

The pool of studies into spatial differences and potential changes in the Baltic Sea wave properties was very limited when work on this thesis started. The first contemporary reconstruction of the wave climate in the Baltic Proper for the years 1947–1988 (Mietus and von Storch, 1997) showed clear seasonal and multi-annual variations in the reconstructed time series but revealed no statistically significant long-term trends.

Wave data obtained from Almagrundet in 1978–2003 revealed that the annual mean wave height had a linear rising trend of 1.8% per year in 1978–1995 (Broman et al., 2006). This trend matched the temporal behaviour of the wind data from the island of Utö in the northern Baltic Sea. The trends extracted from the data for 1993–2003 were less reliable. In particular, the rapidly falling trend in the annual average wave height in 1999–2003 did not match the relevant wind data and was thought to be fictitious. Augustin (2005) identified an increase of 0.3 m in the annual 99%-ile of the simulated significant wave height by in the Baltic Proper at 58º N, 20º E. This feature was mostly caused by an increase in the frequency of severe wave events (BACC, 2008, Ch. 2.3.5).

A review of the existing wave data (Soomere, 2008) concluded that no overall increase in the average wave height occurred in the northern Baltic Proper during the second half of the 20th century. The results of Paper I show that the annual mean wave heights had an almost synchronous behaviour at Almagrundet and at Vilsandi. The rapid increase until the mid-1990s was replaced by an equally rapid decrease at both sites in about 1997. The timing of these variations matches well an almost twofold increase in the number of low pressure observations below 980 hPa at Härnösand for the 1990s (Bärring and von Storch, 2004) and, thus, may simply reflect a change in the trajectories of cyclones for a decade or so. Moreover, the decrease in wave activity since the mid-1990s also matches the decrease in the intensity and duration of severe wave heights in the North Sea since about 1990–1995 (Weisse and Günther, 2007). The frequency of extreme wave storms has been largely stable during the last 30 years (Soomere, 2008). Such storms have occurred roughly twice a decade.

In parallel, Kelpšaite et al. (2008) compared a small subset of visual observations at three Lithuanian coastal sites during 1993–2005 with data from Almagrundet and Vilsandi (Paper I) with the goal of identifying sub-decadal and decadal changes in the wave climate. They showed that wave activity did not change much at the south-eastern coast of the Baltic Sea in the 1990s.

For certain locations along the Estonian coast the basic properties of the wave climate have recently been evaluated using a parametric fetch-based model forced with one-point wind data from the coastal meteorological stations. The research demonstrates that the average wave intensity changes quasi-periodically and reveals no statistically significant trend (Suursaar and Kullas, 2009a, 2009b;

Suursaar, 2010). Part of these studies is reflected in Paper II. Quite large variations in the average wave periods (from about 2.3 s in the mid-1970s to 2.65 s around 1990) have been detected for selected sites (Suursaar and Kullas, 2009a). This is apparently a local effect as numerical simulations of Räämet (2010) revealed no substantial changes either in the most frequent wave periods or in the frequency of occurrence of different periods (Soomere et al., 2011b). Given the forcing of the fetch-based models with one-point wind, it is not surprising that the wave and wind properties were highly correlated.

1.3. Visual wave observations in the Baltic Sea

Historically, visual wave observations from ships have been the primary source of information about the sea state and the properties of ocean waves (Hogben et al., 1986). These data, however, always include intrinsic quality and interpretation problems as described in more detail in Papers I and III. First of all, they always contain an element of subjectivity. This element can be to some extent diminished by specialized training of observers and by using some aids such as fixed moorings or perspectometers but it still remains a major source of uncertainties because of a short observation interval. Visually observed data sets are usually not homogeneous in space and time, have many gaps caused by inappropriate weather conditions and often have a poor spatial and temporal resolution as observations were normally made just a few times a day. The observers are usually incapable of properly quantifying complicated wave systems such as crossing wave systems or combinations of seas and swells (Badulin and Grigorieva, 2012).

The outcome of historical wave observations from ships has been extensively used in the Baltic Sea basin (Davidan et al., 1985). Combined with the results of semi-empirical hindcasts, it has been generalized during preparation of several generations of wave atlases for the Baltic Sea (Rzheplinsky, 1965; Russian Shipping Registry, 1974; Lopatukhin et al., 2006a) and its sub-basins (Rzheplinsky and Brekhovskikh, 1967; Sparre, 1982). As the atlases published before the 1980s were mostly based on outdated understanding of the physics and dynamics of ocean waves (see Komen et al., 1994 for the contemporary perception), they may provide a somewhat different reflection of some properties of the wave climate compared to contemporary sources.

While the data recorded from various ships and often by inexperienced observers are mostly consistent the instrumental measurements (Gulev and Hasse, 1998; 1999), the use of observations from shallow-water and coastal sites raises several additional problems. They evidently inadequately reflect waves in cases when the wind is directed offshore. Coastal observations obviously give a distorted impression of extreme wave conditions because of wave refraction, breaking, reflection and frequency shift in shallow water, or because of the presence of landfast ice. Perhaps the largest issue is that coastal wave observations are extremely site-specific. Strictly speaking, they represent only wave properties in the nearshore in the immediate vicinity of the observation point and for a limited range of directions. This feature makes it often impossible to reconstruct the open sea wave fields from the data observed at nearshore locations. For example, visual wave data from Tallinn Harbour were found to only represent wave properties in the near-coastal regions (Orlenko et al., 1984). They usually missed the long-wave systems (in particular, swell-dominated wave fields), although such fields formed a large part of wave conditions in Tallinn Bay (Soomere, 2005).

These shortcomings are, in fact, not unique to wave observations. For example, coastal measurements of wind properties often give quite a distorted picture about the open sea wind properties (Soomere and Keevallik, 2003). In specific cases it is completely impossible to reconstruct the open sea wind fields from data measured at certain locations (Keevallik, 2003b).

Yet, visually observed wave data are one of the few sources for detecting the wave climate and its long-term changes. Their basic advantage is the large temporal coverage. For example, records of hydrometeorological parameters at Tallinn Harbour started in 1805 and occasionally contained visually estimated wave parameters (R. Vahter, personal communication, 2003). The first wave data from the island of Ruhnu in the Gulf of Riga date back to 1896. Visual wave observations at signal stations have been carried out for about 140 years in the southern Baltic (Rosenhagen and Tinz, 2013). Regular visual observations that started in the mid-1940s in many locations of the eastern coast of the Baltic Sea have been conducted with the use of a unified procedure until today.

The archive of the signal stations of the German Weather Service (Deutscher Wetterdienst) contains hundreds of handwritten diaries over the 123-year-long time interval 1877–1999 (Rosenhagen and Tinz, 2013). Signal stations were positioned close to the seashore along the entire German Baltic Sea coast, from Flensburg up to Klaipėda (Memel), with a major task to warn sailors of severe weather conditions. Although the wind conditions were of particular interest for the sailors, the records often contain information about wave properties. Most of the data have not been digitized yet (Rosenhagen and Tinz, 2013).

Regular visual wave observations have been performed also in Danish waters, mostly from lightships anchored at multiple locations (including Gedser Rev and Halsskov Rev) and a permanent station at Drogden. Observations from Drogden continued until 1994. Typically, 6–8 observations were performed each day (Sparre, 1982; Hünicke et al., 2013). The ships were located at shallow sites of particular danger to ship traffic. Also, the lightships have been moved by short distances on several occasions. This may affect the wave field statistics but gradual changes in wave properties should still be identifiable. As typical of visual observations, the recorded data sets contain some gaps but they still constitute a unique source of retrospective information on the wave climate in the western Baltic Sea. Most of the outcome of visual wave observations from the coast is infrequently used in wave climate studies simply because the relevant data have not been digitized yet. According to Hünicke et al. (2013), the data from Danish waters from 1931 to until the withdrawal of the ships in the 1970s and 1980s, used in Sparre (1982), are digitized.

In the described perspective, the historical visual wave data from the eastern parts of the Baltic Sea form an extremely valuable data set for the identification of changes in the local wave climate because of their relatively high quality and extremely long temporal coverage. Similarly to the generic problems with visual wave observations there is some uncertainty about the significance of various factors (such as observer's error or subjectivity, or noise in the data; see above and Paper I) affecting the observed changes. Still, in cases where major changes extracted from visual observations occurred simultaneously and with a similar relative range to those obtained from instrumental measurements (cf. the variations in the wave height in Broman et al. (2006) and in Paper I), it is very likely that the changes observed at the coast do represent the processes on the open sea.

1.4. Wave observations from the eastern coast of the Baltic Sea

The eastern Baltic Sea is one of the few areas where systematic visual wave observations have been performed at numerous locations during a long time using an identical observation procedure. Some of these observations are going on also today. In this thesis I consider the data filed at hydrometeorological stations of the former USSR and using the same routine starting from the mid-1950s. These records provide an exceptionally long temporal and relatively good spatial coverage. Several data sets of wave heights have recently been reconstructed back to 1946 using a high correlation between the wave height and qualitative measures of sea state (Soomere, 2013). As will be demonstrated below, these data sets not only successfully reproduce the basic features of the wave climate at the site but also give an overview of seasonal cycles, interannual variations and spatial patterns of long-term changes in certain wave parameters (Soomere et al., 2011).

From a total of 12 data sets that have been digitized by now, I focus on the data from four Estonian sites and one Lithuanian observation site (Figure 1). A detailed description of the observation sites, the used routine and data pre-processing is available in Papers I–V and I present here only the key information. I occasionally use also the data from Liepaja and Ventspils that were analysed using the methodology employed in Papers I, II and V and were published in Pindsoo et al. (2012) and Soomere (2013). The overview of the relevant data sets is presented in Table 1.

The site on the western coast of the island of Vilsandi (58°22′59″ N, 21°48′55″ E) in the Western Estonian archipelago is known for its ability to reasonably reflect the predominant wind directions (SW and NNW, Soomere and Keevallik, 2001) in the northern Baltic Proper. These data are frequently used in simulations of waves, water level or circulation patterns (e.g., Suursaar et al., 2006). This island is also named Felsland on older maps after a limestone cliff along its western coast. Meteorological observations have a long tradition on this island. The first data are known from September 1865 but observations have evidently been performed also earlier. The collected data satisfactorily reflect wave conditions for the predominant wind directions but are definitely inadequate for easterly winds (which are relatively weak and infrequent in this area, Soomere and Keevallik, 2001). As the water depth is only 3–4 m in the area where waves are observed, the highest waves may experience a heavy impact of bathymetry and may already be breaking. For this reason, observations of unreasonably high waves are discarded from the data set (Paper I).

Table 1. Basic parameters of wave observations at Vilsandi, Pakri and Narva-Jõesuu. Notice that the difference between the average values of the maximum and mean wave heights is partly connected with the availability of these parameters for different time intervals.

		Vilsandi 1954–2008	Pakri 1954–1985	Narva-Jõesuu 1954–2008	Nida 1954–2008
Co-ordinates		58°22′59″ N 21°48′55″ E	59°23′37″ N 24°02′40″ E	59°28′06″ N 28°02′32″ E	55°19′ N 28°02′ E
Nearest grid point of the wave model WAM (Räämet, 2010)		58°24′ N 21°48′ E	59°24′ N 24°00′ E	59°30′ N 28°00′ E	
Consistent wave height entries	total	27 131	13 283	35 027	48 237
	days covered	15 977	9554	15 863	19 474
Consistent wave period entries	total	28 016	10 354	8488	8618
	days covered	12 553	7724	3514	3469
Largest maximum/mean wave height, m		8/7.6	6/6	3.4/3.3	–/5.2
Average of the maximum wave heights, m	total mean	0.584	0.616	0.455	0.719
	mean of daily values	0.621	0.610	0.462	0.727
Average of the mean wave heights, m	total mean	0.511	0.591	0.393	0.694
	mean of daily values	0.539	0.589	0.391	0.702
Mean wave height based on mean of daily values		0.575	0.590	0.391	0.701
Number of calm conditions		11 417	1923	4692	342

As the station was occasionally used for training purposes, at times the observations were performed by inexperienced observers and thus may contain relatively large uncertainties (T. Kõuts, personal communication, 2013). Another source of somewhat reduced quality of wave data at this site is the practice of using two alternative observation points. The properties of waves approaching from the western and partially from the northern directions (SW–NNE) are observed from a coastal site located about 1.5 m above mean water level. For waves approaching from more southern directions, an observation point at a light pier was used.

The observed wave properties represent well the open sea conditions for northerly wave directions at Pakri (59°23′37″ N, 24°02′40″ E) in the western part of the Gulf of Finland. The data were first analysed and published in Paper II. The average depth of the area over which the waves were observed was 8–11 m and thus shallow water effects on wave propagation were relatively modest. Waves were observed from a steep cliff 24 m above mean sea level. The Pakri data set contains evidence of the roughest ever reliably recorded wave conditions in Estonian coastal waters. Namely, the wave height of 6 m was registered twice each day on 6–7 August 1967 (Paper II) when a strong north-western storm excited extremely rough wave conditions and caused extensive damage to the forests. Unfortunately, wave observations were only performed in 1954–1985. The station was relocated several times (Keevallik and Soomere, 2009; Zujev, 2013), which makes the analysis of wave approach directions quite complicated (Paper V).

The wave observation site of the Narva-Jõesuu meteorological station is located on the coast of Narva Bay (59°28′06″ N, 28°02′32″ E) and provides information about wave fields in the eastern part of the Gulf of Finland. The site from which sea observations are made is located to the west of the station and is fully open to waves propagating from the NW direction and almost open to waves approaching from the west to north. The presence of a large river mouth allows a wide range of wave approach directions for observations (Paper III). The height of the first observation platform (12.8 m above mean sea level) ensured a good sight over the wave observation area located about 200–250 m from the coast and at a sea depth of 3–4 m. As waves in the Gulf of Finland are generally much lower than in the Baltic Proper, they normally do not break in the observation area. When this platform was damaged (in 1970), the observation site was relocated a bit closer to the waterline. A buoy was deployed to the observation area in the sea in 1971 to help the observer. Since 1977 the observation site has been moved on the crest of a dune at a height of 9 m above the mean sea level (Zujev, 2013). As expected, the maximum wave heights were much lower at Narva-Jõesuu where they exceeded 3 m only four times. The largest maximum/mean wave heights (3.4/3.3 m) were recorded on 25 October 1957 and twice on 28 August 1961.

The geometry of the coastline at Nida (55°19′ N, 21°01′ E) in the northern part of the Curonian Spit (the south-eastern part of the Baltic Sea) allows proper observations of the waves approaching from the south-west to north. These directions represent the largest fetch. The observer was standing at a turret located 7 m above mean water level at the coast and observed waves in an area located about 700 m from the coastline at a water depth of 6–7 m. A short section of the data from Nida was used in the analysis of Kelpšaitė et al. (2008) and the bulk of the data was presented in Paper V.

At Palanga (55°55′ N, 21°03′ E), observations were made from the Palanga Sea Bridge, about 3 m above sea level, which extends 470 m offshore where the water depth area was 6–7 m. The site is open to the wave directions from the south-south-west to north-north-west. At Klaipėda (55°42′ N, 21°07′ E), observations were made from the coast. The observer was standing about 3 m above sea level and observed an area that lies about 500 m off the coast. This site is also open to the wave directions from the south-west to north-north-west. Observations at the Lithuanian coast were made using the same methodology as at the Estonian coast (Kelpšaite et al., 2008).

The analysis of visually observed wave data from three Lithuanian sites (Nida, Palanga and Klaipėda) for 1993–2008 shows that the changes to the annual mean wave height are almost synchronous there. This is not unexpected as the sites are located on the open slightly curved <90 km long section of the coast (Kelpšaitė et al., 2008) and spatial changes in the wave climate have a typical scale of at least 200 km for the Baltic Proper (Soomere and Räämet, 2011a). For this reason, in Paper V the data from Nida are chosen to represent the wave climate and its changes for the entire coast of Lithuania.

As discussed in detail in Papers I–V, all study sites are coastal and thus only conditionally represent open sea conditions. Although these sites are fully open in some directions and waves in the Baltic Sea are relatively short and thus less affected by finite-depth effects than much longer ocean waves at similar depths, the sheltering effect of the shoreline and a relatively small water depth may at times significantly alter the local wave regime compared to that in the open sea due to the shoaling, refraction, reflection and damping of the waves.

The wave observation routine was identical at all visual observation sites. The number of observed parameters varied greatly in different years. During various years of observations (i) the qualitative sea state, (ii) the general appearance of the wave field, (iii) the wave direction, (iv) the intensity of waves, (v) the maximum and (vi) mean wave height, (vii) wave steepness, (viii) length and (ix) period were recorded (Guidelines, 1985). Not all of the recorded parameters are independent, and in the course of time their number was reduced. The data about the wave height, direction and period have the largest temporal coverage. A link between the qualitative sea state and the wave height (Soomere, 2013) made it possible to reconstruct changes in the wave heights back to the mid-1940s. Also, several qualitative measures were helpful in estimates of the consistency of data (Paper I).

The entire procedure relies on the detection of single waves and their properties similarly to the classical zero-crossing method (IAHR, 1989). The observer noted the five highest waves during a 5-min time interval. The accuracy of specification of their height was 0.25 m for wave heights ≤1.5 m, 0.5 m for wave heights from 1.5 to 4 m and 1 m for even higher waves. Both the height of the highest single wave H_{max} (called maximum wave height) and the mean height H of these five waves were filed until about 1990.

Typical wave periods in the coastal zone of the Baltic Sea are 2–4 s (Broman et al., 2006, Papers I, II, V, Soomere et al., 2012). Therefore, the maximum wave height is approximately equal to the average height of 2.5–3% of the highest waves and the mean wave height is approximately equal to the average height of 5–7% of the highest waves. A certain overestimation of the wave height compared to a record at a fixed point may stem from a wish of the observer to recognize clearly separable largest waves over the entire observation area (T. Kõuts, personal communication, 2013). A comparison of the outcome of visual observations with numerical studies in Papers III and IV suggests that such an overestimation was negligible in terms of overall wave statistics.

The wave period (or length) was determined as an arithmetic mean from three consecutive observations of the passing time (total length) of 10 waves each time. These waves were not necessarily the highest ones. The visually observed wave period is usually only a few tenths of seconds shorter than the peak period (Gulev and Hasse, 1998, 1999). For that reason, we shall interpret the visually observed wave period as an estimate of the peak period.

The wave direction was defined (with a resolution of 45°) as the direction from which the waves approached. For a combination of windseas and swell, or for cross-seas, the wave parameters were given for the dominating component.

Wave observations were only performed during daylight hours. The initial time of observations in the 1950s and 1960s (7:00, 13:00 and 19:00 Moscow time, GMT +3 h, Guidelines, 1985) was shifted to 6:00, 12:00 and 18:00 GMT according to the World Meteorological Organization (WMO) guidelines in 1991 (WMO, 2001). As the diurnal variations in the wave height are very small in the Baltic Sea (Pindsoo et al., 2012; Soomere et al., 2012), this shift apparently has no great impact on the quality and homogeneity of the data.

2. Observed wave climate

This chapter discusses the major features of the Baltic Sea wave fields extracted from visually observed data sets. The presentation of these aspects mainly follows Papers I, II and V where most of these data sets were first published in international literature. The use of wave observations from coastal sites for wave climate studies is not straightforward and much more complex pre-processing of the observed wave data than standard meteorological variables is needed. Reliable estimates of the wave climate also generally require a combination of different data sources with extensive modelling resources. For this reason the results of visual wave observations are systematically compared with measured and modelled data following the relevant material in Papers II, III and IV. The major outcome of the analysis is of course not surprising: the visually observed wave data sets represent well the general features of the Baltic Sea wave fields, first of all the relatively low overall wave activity, short wave periods, the overall shape of the distributions of the basic wave parameters and substantial seasonal variation in wave conditions (Soomere, 2008; Hünicke et al., 2013).

2.1. Pre-processing and interpretation of visually observed wave data

As discussed above and in all papers on which this thesis is based, visual wave observations, albeit forming an important source of information about the sea state in the past, have several obvious shortcomings. Nevertheless, large pools of visually observed data from ships adequately reflect the basic wave features in the open sea (Gulev and Hasse, 1998) and are extremely useful for reconstructing long-term changes in wave properties (Gulev et al., 2003; Gulev and Grigorieva, 2006). Wave observations from coastal sites are more problematic because the results inherently reflect a multitude of processes of wave transformation in the nearshore. There is thus a need for much more complex pre-processing of the observed wave data than standard meteorological variables such as pressure, temperature or wind speed (Soomere, 2013).

The interval between subsequent observations (6–24 h depending on the season) is often much longer than the typical saturation time of rough seas (about 8 h, Soomere, 2001) in the northern Baltic Proper. The duration of a wave storm seldom exceeds 10 h in this area (Broman et al., 2006; Lopatukhin et al., 2006a, 2006b). Therefore even the strongest storms, if they were not long enough, or occurred during a night, or were accompanied by low visibility, are not necessarily represented in the data set. Consequently, the observations cannot be used for the reconstruction of the time series of the sea state. Instead, they should be interpreted as a set of regular samples reflecting the sea state. Since the number of observations is quite large (usually 30 000–50 000 at each site, Table 1), the data apparently reflect the basic features of the wave climate at the site even if the uncertainty of each single observation is relatively large.

This procedure of data pre-processing is described in detail in Paper I. As a first step, all obviously erroneous or ambiguously written entries were omitted. The digitized data sets were then checked for internal consistency (e.g., whether large wave heights are associated with relatively large periods). Clearly inconsistent records (e.g., the wave height was >1 m but the sea state was marked as nearly calm) were discarded. Many records of the wave height formulated as <0.25 are available in older diaries. They have been digitized as 0.25 m, because completely calm seas are infrequent in the Baltic Proper (Broman et al., 2006).

The water depth at the location where the wave properties were determined was often such that the highest waves were already in the breaking stage. This is the probable reason why in some diaries (most notably at Vilsandi) unrealistically large wave heights exceeding the water depth in the observation area have been reported. All such observations were made in quite strong wind conditions and the maximum and mean wave heights were in a reasonable balance. Therefore, it is likely that they corresponded to a certain overestimation of wave heights in very rough seas. Such observations were either discarded or corrected to physically reasonable values in the evaluation of long-term wave properties. The original values were only kept in the scatter diagrams of all observed wave conditions. The number of such cases was very small (a few tens per observation site; <0.1% of the total number of sensible observations) and the use of either approach insignificantly affected the wave statistics.

Wave height recordings over years showed some inconsistency at almost all measurement sites. Usually the diaries contain both the maximum and mean wave heights during the first years of observations, further on, however, only one measure although the two entries appear at times (Paper I). In the analysis of the wave data, the mean wave height is commonly used; when it was missing, it was substituted by the maximum wave height. The maximum wave height was, on average, only by 6% higher than the mean wave height at Vilsandi (Paper I). The difference between these quantities is thus much smaller than the accuracy of the determination of the wave height and it is very likely that such a substitution insignificantly affects the wave statistics.

As the observers' estimates represent the significant wave height well (Gulev and Hasse, 1998; 1999), the visually observed data are often interpreted as estimates of the significant wave height. As swells of considerable height are infrequent in the Baltic Sea (Broman et al., 2006), the wave approach direction normally represents the direction of the windseas.

The data sets have several gaps. At least one sensible observation exists at these sites, on average, on about 80% of all the calendar days. Some of the gaps stem from shutting down the relevant meteorological station (e.g., July–September 1991 when the Vilsandi station was closed) or simply from omitting the observations in the 1990s (Figure 2). A larger number of gaps result from the impossibility of carrying out observations either because of darkness or the presence of sea ice. Such gaps are characteristic of more northern stations such as Vilsandi, Pakri and Narva-Jõesuu (Figure 3) where the data coverage varies greatly in different years and seasons. Systematic gaps from January to March are evidently connected with the presence of sea ice at these sites. On top of that, the number of sensible observations made at different observation times varies considerably in the northern Baltic Sea and in the Gulf of Finland (Papers I, II, V).

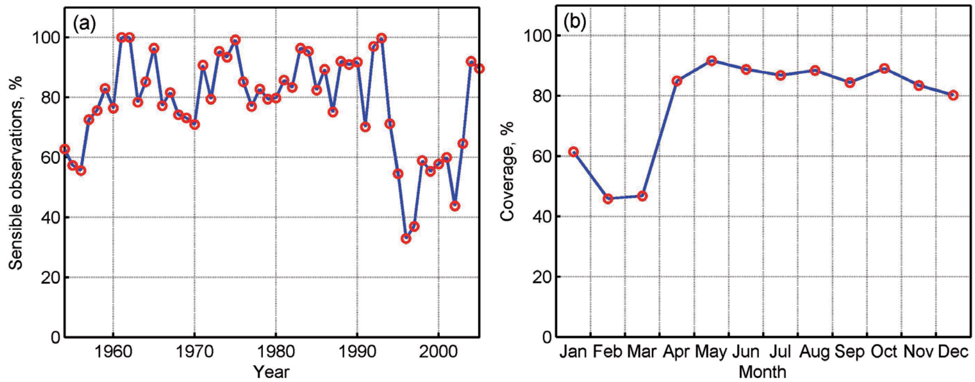

Figure 2. Percentage of days with at least one sensible wave observation at Vilsandi: (a) in years 1954–2005, (b) in different months (Paper I).

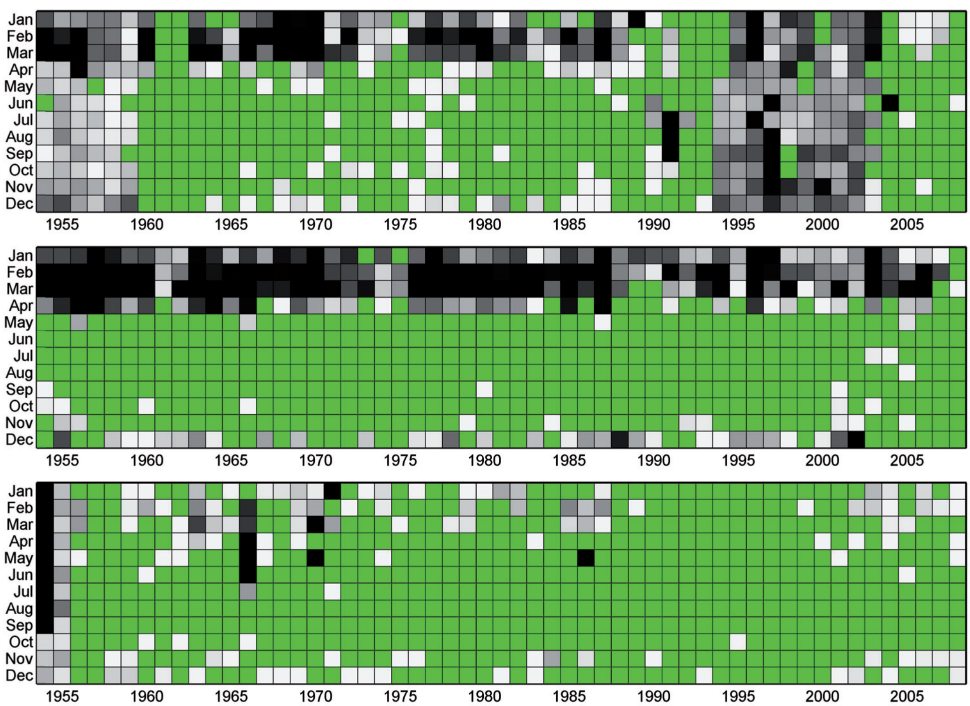

Figure 3. The proportion of days with at least one sensible wave observation at Vilsandi (upper panel, Paper I), Narva-Jõesuu (middle panel, Paper III) and Nida (lower panel). High coverage is indicated in white, the 100% coverage in green and low coverage corresponds to dark grey.

The majority of observations have been made at these sites at noon. Morning and evening observations are more fragmentary. Usually more observations a day were performed during the relatively calm spring and summer seasons than during the relatively windy autumn season. Therefore, a direct use of the full set of observations may lead to a bias in statistics of wave height stemming from the different number of observations per day in seasons with different wave properties. Relevant research (Pindsoo et al., 2012; Soomere et al., 2012) has shown that daily variations in wave properties are very small in the eastern and southern regions of the Baltic Sea. The formal average wave height of all sensible observations at Vilsandi is, however, 0.49, 0.57 and 0.42 m for the morning, noon and evening measurements, respectively (Paper I). Based on these arguments, the potential bias in the long-term average wave height is eliminated by means of using the daily mean wave height (over 1, 2 or 3 sensible observations) at all sites.

As the number of sensible observations of other parameters is clearly smaller and several parameters (such as wave period or approach direction) are not additive, the full set of the relevant data is used in Papers I–III and VI. The results largely represent Type A statistics in terms of the classification of Kahma et al. (2003) and Tuomi et al. (2011). Except for using an average of the available wave height observations on each day in some parts of the analysis, no corrections have been made to compensate for missing values, for the uneven distribution of data or for ice cover. In particular, all observed values of the wave height are used to construct the joint distributions of wave heights and periods.

2.2. Comparison with the output of wave models

A variety of different wave models are available. Their examples range from simple models that estimate only certain wave properties for the given geometry of the basin based on a time series of locally measured wind information to contemporary spectral models that are able to adequately account for all major drivers of wave generation, interaction, decay and transformation. The latter models describe the wave fields in terms of a wave spectrum, which shows how the wave energy is shared between components of different length and propagation directions.

The presented outcome of visual wave observations is compared against the results obtained with a locally calibrated hindcast using a fetch-based model (Paper II), and with the data from the WAM model forced with adjusted geostrophic winds (Papers III, IV).

The calculation of wave parameters near the Harilaid Peninsula (at a location about 1–1.5 km off the coast and 7 km to the north of the Vilsandi observation site) was based on the fetch-limited equations of Sverdrup, Munk and Bretschneider (SMB-model; see, e.g., Seymour, 1977; Huttula, 1994) developed and run by Dr. Ü. Suursaar. The model was forced by wind data from Vilsandi for 1966–2006 and accounted for the effective fetch and water depth. It calculates the time series of significant wave height, wave period and wavelength for the chosen location. In shallow, nearshore areas with complex shoreline geometry and bottom topography, long-term hindcast simulations with more up-to-date wave models may be time-consuming and complicated. In such conditions, fetch-limited point models may offer a simple alternative (Özger and Sen, 2007). The model was calibrated using *in situ* data from a measuring complex RDCP-600 (Aanderaa Data Instruments) that was deployed to the seabed at the same location (58°28′ N, 21°49′ E) for which the wave calculations were made. The mooring depth was about 14 m. A more detailed overview of the calibration procedure is presented in Paper II and Suursaar and Kullas (2009a).

The outcome of the analysis of visually observed data was also compared with wave properties computed using the WAM model Cycle 4 (Komen et al., 1994). This model was run by A. Räämet over 38 years for 1970–2007 (Räämet, 2010). It is commonly accepted that the WAM model gives good results in the Baltic Sea if its resolution is appropriate and the wind information is correct (e.g., Augustin, 2005; Schmager et al., 2008; Tuomi et al., 2011). The WAM model was run in the shallow-water mode with depth refraction in order to match realistic wave propagation over the highly variable bathymetry of the relatively shallow Baltic Sea. The bathymetry was based on data prepared by Seifert et al. (2001) and has been adjusted as described in Soomere (2001). The calculations were performed for the entire Baltic Sea. The sea was covered by a regular rectangular grid with a resolution of about 3×3 nautical miles (3′ for latitude and 6′ for longitude).

At each sea point 1008 components of the 2D spectrum were computed. The spectrum represented wave components corresponding to 24 equally spaced directions (with the angular resolution of 15°) and 42 frequencies from 0.042 Hz (23.9 s) to about 2 Hz (0.5 s). Such an extended frequency range up to 2 Hz was used to ensure realistic wave growth in low wind conditions that often occur in the Baltic Sea (Soomere, 2005). The wave model was forced with wind data constructed on the basis of geostrophic winds provided by the Swedish Meteorological and Hydrological Institute (SMHI). An approximation of the near-surface wind at the 10 m level was calculated following a procedure in which the geostrophic wind speed was multiplied by 0.6 and the direction turned 15° anticlockwise (Bumke and Hasse, 1989). A detailed validation of the model results was performed using wave statistics from Almagrundet and several data segments from waverider measurements in the northern Baltic Proper by Räämet et al. (2009) and Räämet and Soomere (2010). The wave model reasonably reproduces the time series of wave properties (Räämet et al., 2009). The maximum wave heights are somewhat overestimated for some storms and underestimated for other wind events. Detailed information about the model setup, validation and performance is available in Räämet (2010).

2.3. Distributions of wave heights, periods and approach directions

As discussed above, the analysis of wave heights largely relies on the daily average wave height, calculated as an arithmetic mean of sensible observations of each day.

The long-term average wave height, calculated using this approach, is 0.575 m at Vilsandi, 0.59 m at Pakri, 0.39 m at Narva-Jõesuu and 0.73 m at Nida (Table 1). These values are clearly smaller than the mean significant wave height at Almagrundet (0.876 m in 1978–1995, 1.04 m in 1993–2003, Broman et al., 2006). The wave height median values at all sites (0.3, 0.5, 0.35 and 0.45 m for Vilsandi, Pakri, Narva-Jõesuu and Nida, respectively) are also much smaller than at Almagrundet. This difference is natural as all the observation sites are coastal and therefore sheltered from some directions. This feature becomes also evident as a relatively large number of almost calm days at all observations sites. The presented mean values in some cases reflect different time intervals and thus are not always directly comparable.

The observed long-term wave heights match the numerically reconstructed wave heights (Table 2) quite well (Paper III; Räämet, 2010). The comparison of heights, however, is not straightforward because the time intervals covered by the hindcast and observed data only partially overlap. For the overlapping time intervals the observed and modelled average wave heights at Vilsandi differ by less than 1 cm (<2%) over the period 1970–2007 (Table 2). The match is of almost the same quality at Pakri for 1970–1985. The overall observed wave height at Pakri in 1954–1985 is very close to that calculated for 1970–2007 (Table 2). As the observed wave heights represent the areas quite close to the coast where the wave height usually is clearly smaller than in the model grid cells, the described feature has been interpreted as showing that the model configuration in Räämet (2010) to a certain extent underestimates the long-term average wave height.

Table 2. Average wave heights at the measurement sites in the northern Baltic Proper and the Gulf of Finland. For the visual observation sites the average of daily mean values is presented (Papers I, II).

Site	Years	Average wave height, m	
		Observed or measured	Hindcast (Räämet, 2010)
Almagrundet	1978–1995	0.876	0.714
(Broman et al., 2006)	1993–2003	1.040	0.705
Vilsandi	1954–2008	0.575	no data
	1970–2007	0.560	0.563
Pakri	1954–1985	0.591	no data
	1970–1985	0.571	0.569
	1970–2007	no data	0.584
Narva-Jõesuu	1954–2008	0.390	no data
	1970–2007	0.368	0.466

The observed wave heights are clearly smaller than the hindcast ones at Narva-Jõesuu. This is evidently caused by a combination of the location of the model grid point far (about 4 km from) from the observation site in much deeper water (about

7 m, Papers III, IV) and the presence of ice (that is not accounted for in the model) during a large part of the year.

One of the basic properties of the wave climate is the frequency of occurrence of wave conditions with different parameters. This property is usually characterized using empirical distribution functions. Unlike the analysis of average wave heights, these distributions reflect all consistent observations of wave heights with non-zero wave periods and thus to some extent overestimate the proportion of relatively low wave conditions in seasons with a longer duration of daylight.

The frequencies of occurrence of different wave heights vary considerably at different sites (Figure 4). At Vilsandi and Narva they reveal a high proportion of low waves with heights below 0.25 m and resemble analogous distributions for wave heights in semi-sheltered bays of the Baltic Sea (Soomere, 2005). Such distributions differ largely from an analogous distribution at Almagrundet (that resembles the Rayleigh distribution, Broman et al., 2006). Although the frequencies of the highest waves at these sites are not directly comparable, the probability of occurrence of the wave height $H \geq 4$ m at Vilsandi (~0.2%) matches well an analogous probability (about 0.42%) at Almagrundet in 1978–2003. On the contrary, this distribution at Pakri matches the ones for Almagrundet and the northern Baltic Proper (Broman et al., 2006; Soomere, 2008). This feature suggests that the observed wave properties at Vilsandi are quite strongly affected by the presence of the coast while the observations at Pakri better represent offshore wave properties.

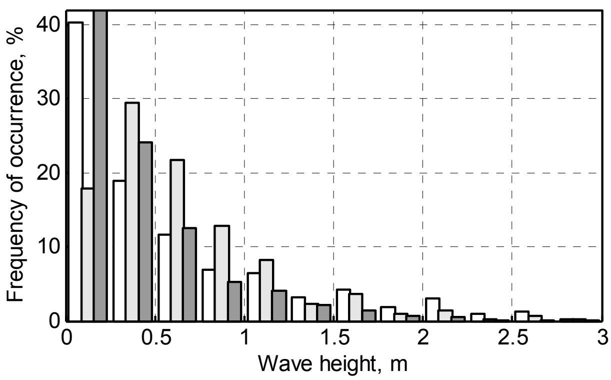

Figure 4. Frequency of occurrence of different wave heights (resolution 0.25 m) at Vilsandi (white bars), Pakri (light grey bars) and Narva-Jõesuu (dark grey bars).

A comparison of the distributions of observed and modelled wave data reveals a relatively large difference between modelled results if the step in wave heights is below 0.5 m (Papers II, IV; Räämet, 2010). While this distribution at several sites (especially Narva-Jõesuu and Vilsandi) has a clear maximum for waves with heights below 0.25 m, the modelled distributions (Figure 5) exhibit similarity to a Rayleigh distribution (that is characteristic of offshore domains, Soomere, 2008).

The frequency of the observed (36%) and modelled (44%) low wave heights (below 0.5 m) differ only insignificantly. While waves with heights around 1–1.5 m are sensibly reproduced, the frequency of even higher waves is underestimated by models. These differences may be attributed to changes in wave properties in the nearshore: visual observation points are located much closer to the coast than the relevant centres of the model grid cells and thus often reflect extensive wave shoaling. Another possible reason for the mismatch between the modelled and observed distributions is the sea-breeze that is ignored in model calculations. Also, ice conditions frequently impact the sea state at these sites (Sooäär and Jaagus, 2007).

A slightly different pattern of discrepancies exists between the central area of the northern Baltic Proper and the coastal area of Lithuania (Räämet, 2010). The WAM model adequately captures the frequency of calm conditions and reasonably hindcasts relatively rough windseas but significantly overestimates the frequency of the most typical wave conditions with a height around 0.5 m. Interestingly, the WAM model gives one of the best matches of the distributions in question with observations at Pakri, suggesting that this site has good potential for representing wave conditions in the region.

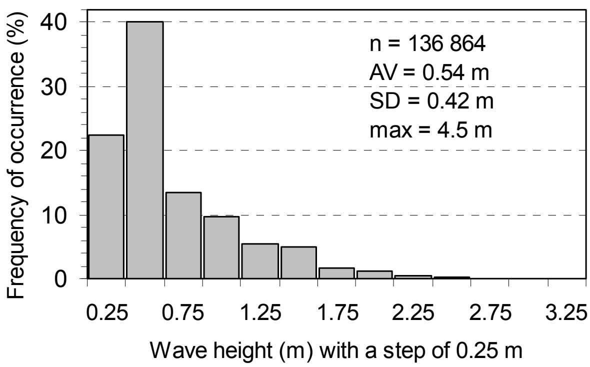

Figure 5. Frequency of occurrence of significant wave heights in hindcast data in 1966–2006 at a location near Harilaid, about 7 km from the Vilsandi observation site (Paper II, data and graphics by Ü. Suursaar).

The distributions of wave periods presented in Figure 6 also involve all sensible observations and are thus similarly biased as the distributions for wave heights. Moreover, wave periods are not always recorded in visual observations (Kelpšaite et al., 2008) and are not usable in some measured wave data sets (Broman et al., 2006). As these distributions tend to have a very stable shape in time (Soomere et al., 2012), the presented ones can be considered as representative for the relevant sites. All these distributions have a general shape that matches a similar distribution for offshore waves in the northern Baltic Proper (Kahma et al., 2003).

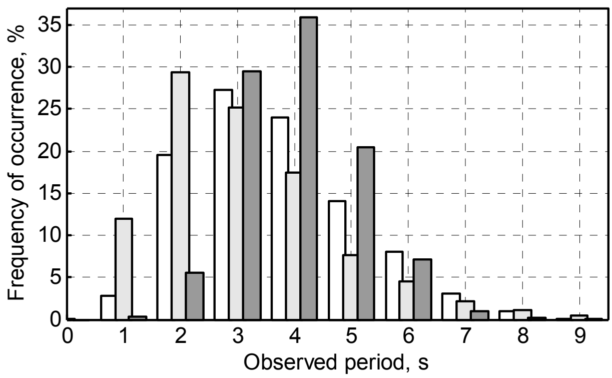

Figure 6. Frequency of occurrence of different observed wave periods (resolution 1 s) at Vilsandi (white bars, Paper I), Pakri (light grey bars, Paper II) and Narva-Jõesuu (dark grey bars, Paper II).

The most common wave periods are 2–4 s at Vilsandi and Pakri, with the largest number of waves with a period of 3 s. As will be demonstrated below, they correspond to low, about 0.5 m high waves. Typical periods are slightly longer, 3–5 s at Narva-Jõesuu where they match periods typical of the open part of the Baltic Sea (Kahma et al., 2003). This feature may be explained by the frequent presence of long waves travelling along the axis of the gulf. Such waves are often excited in this water body even when the wind blows obliquely with respect to its axis in so-called slanted fetch conditions (Pettersson, 2004; Pettersson et al., 2010). It is also possible that frequent westerly winds (that have quite a large fetch, >150 km) may bring to Narva Bay appreciable amounts of remotely generated wave energy even from the northern Baltic Proper.

The wave approach direction was recorded with the resolution of 45º. The ambiguity in the use of zero values at different sites and times (calm seas or waves propagating from the north) was resolved based on other measured parameters. A few doubtful cases were left out of the analysis. A relatively large number of wave conditions with zero wave heights but sensible wave directions from the eastern sector filed at Vilsandi apparently represent weak wave fields excited by offshore (easterly) winds. Very few such cases have been recorded at the other sites.

The predominant wave directions (Figure 7) match the two-peak directional structure of the prevailing winds of the northern Baltic Proper (Soomere and Keevallik, 2001) at all observation sites. The particular direction for the peaks to some extent depends on the orientation of the coastline and is evidently also affected by refraction (Viška and Soomere, 2012). At Vilsandi waves mostly approach from the south-west or from the north (the latter direction also involves north-north-west owing to the low directional resolution). Waves approach Pakri mostly from the west (although the site is also fully open to the north), and Narva-Jõesuu – from the west-north-western direction. The modelled distributions follow the same pattern but are to some extent more contrast (with slightly narrower and higher peaks, Paper III) due to the low directional resolution of observations.

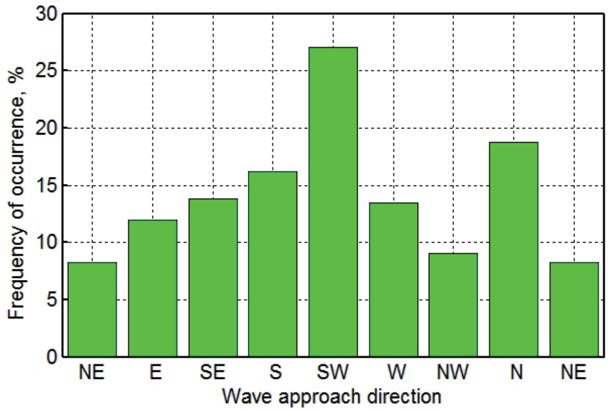

Figure 7. Frequency of occurrence of different wave approach directions at Ventspils in 1954–2011 (Pindsoo et al., 2012).

2.4. Combinations of wave properties

For many purposes it is important to know the occurrence of different combinations of wave heights and periods. This knowledge is crucial, for example, in planning the wave energy plants (Cruz, 2008) and for estimates of the potential impact of the highest and steepest waves to ensure navigation safety (Toffoli et al., 2005). Respective information can be obtained from empirical two-dimensional distributions of the joint frequency of occurrence of wave fields with different heights and periods. Such distributions often enable rough evaluation of the properties of the severest wave storms in the area (Lopatukhin et al., 2006a, 2006b). They are sometimes called scatter diagrams of wave heights and periods (Kahma et al., 2003). The scatter diagrams (yielding distributions of different wave heights and periods by integration over the relevant direction) have been constructed and analysed for different sites in Papers I and III.

Typical combinations of wave properties correspond to the points located at the maxima of these distributions. For the open ocean sites such diagrams usually contain two branches. One of them represents windseas, the other one swells with relatively large periods and moderate heights (Lopatukhin et al., 2006a). The scatter diagrams, however, have a regular shape of an elongated, slightly curved elevation for all observation sites of the Baltic Sea. The most typical wave conditions roughly correspond to fully developed seas with a Pierson–Moskowitz spectrum (Figure 8). The branch representing swells is almost degenerate at all observations sites. It only becomes evident as a pool of waves with periods of 7–9 s and heights around 1 m at Pakri and is almost missing at Almagrundet (Paper III).

The periods of 2–3 s usually correspond to wave heights well below 1 m, whereas waves with periods of 4 s have a typical height of about 1 m. Wave periods of about 5–6 s also occur with an appreciable frequency and usually correspond to wave heights of about 1.5–2 m. Wave fields with periods of about

7 s occur with a frequency of about 3%. The corresponding wave heights are usually close to 2.5 m. Wave periods over 8 s are rare and occur with a probability of about 1%.

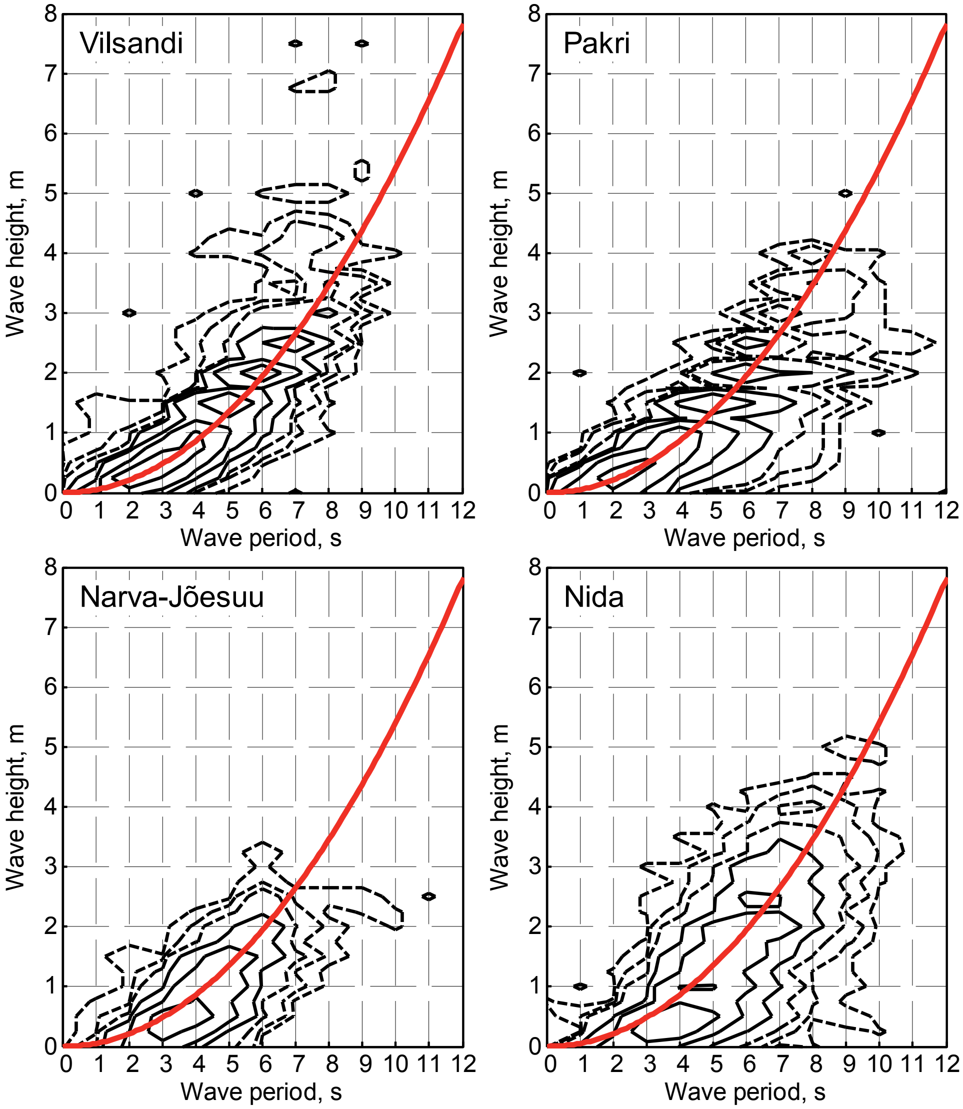

Figure 8. Joint distribution of the observed wave heights and periods at Vilsandi, Pakri, Narva-Jõesuu and Nida. The wave height step is 0.25 m. Isolines for 1, 3, 10 (dashed lines), 33, 100, 330, 1000 and 3300 (solid lines) cases are plotted. The bold line shows the height of the fully developed wave systems with the Pierson–Moskowitz spectrum for the given mean period.

A large part of the observed wave data are represented in Figure 8 by points lying considerably to the left from the curve reflecting the wave conditions with a

Pierson-Moskowitz spectrum. Such points correspond to high and short, thus very steep waves that are frequently associated with acute danger to ships (Toffoli et al., 2005). In the nearshore the combination of shoaling and a decrease in the wave period evidently contributes to the steepening of the observed waves. Still, also wave simulations (Paper III; Räämet, 2010) confirm that the Baltic Sea hosts a substantial proportion of dangerously steep waves. In particular, the instrumental data from Almagrundet, Bogskär and the central part of the northern Baltic Proper (Figure 1, Section 1.2) show that the predominant waves in the roughest seas in the Baltic Sea are generally steeper than in the fully developed wave systems (Kahma et al., 2003; Soomere, 2008). The highest waves ($H_S \geq 7$ m) correspond to mean periods of 8–9 s at Almagrundet and to peak periods of 9–11 s at Bogskär and in the northern Baltic Proper (Soomere, 2008).

The scatter diagrams for the observed and modelled waves are compared in Paper III based on the output of the WAM model for grid cells adjacent to the observation sites. These diagrams are very similar at all observation sites for low and moderate wave conditions, up to wave heights of 3 m. The numerically simulated distributions are narrower. This feature probably reflects the relatively low accuracy of single visual observations. Another source of differences is that the observation site and the nearest grid point of the wave model do not coincide. The largest difference in the shape of the distributions in question is recorded at Vilsandi and probably stems from relatively extensive impact of the nearhsore effects on the waves observed at this site. Therefore, the hindcast distribution evidently provides a more adequate estimate for the wave properties in strong storms at Vilsandi.

Paper III also discusses a simple approach to estimate the most probable combination of properties of the largest waves at the observation sites using the scatter diagrams (cf. Lopatukhin et al., 2006a). Once in about 40 years the highest waves may reach 6.5 m in the deeper nearshore at Vilsandi and about 6 m at Pakri. The corresponding mean wave periods are 11–12 s at Vilsandi but much shorter, about 9–10 s, at Pakri. This difference apparently reflects the longer fetch for Vilsandi. Still, very high waves at Pakri may be excited by severe north-north-western storms (Soomere, 2001; Soomere and Keevallik, 2001) that have a shorter fetch. The scatter diagrams and the properties of maximum waves are very similar at Pakri and Nida. At Narva-Jõesuu already 4 m high waves are extreme. Their period is expected to be about 7–8 s. These estimates reasonably match similar estimates extracted from numerically simulated data (Paper III).

2.5. Seasonal course of wave heights

A key feature of the wind and wave climate of the Baltic Sea is their high seasonal variability (Jönsson et al., 2003; BACC, 2008; Schmager et al., 2008). It is driven by a considerable seasonal variation in the wind speed (Mietus, 1998), which is accompanied by variations in the angular distributions of wind properties in different seasons (Soomere and Keevallik, 2001). The monthly mean wind speeds are usually the highest in autumn and early winter (October–January), while the months are the mildest in late spring and early summer (Mietus, 1998). The variations in the monthly mean wind speed are about ±20–25% of the annual mean. For example at Utö (in 1961–2001) the wind speed was about 5.3 m/s in May–July and >8.4 m/s in December, whereas the mean wind speed was 6.7 m/s. An interesting feature of the seasonal course of the wind speed and wave height is that the windiest season is shifted by about 1–2 months with respect to the season with the largest wave activity in this region (Räämet and Soomere, 2010).

Seasonal variation in the monthly mean wave heights is clearly evident at all observation sites (Figure 9; Papers I, III, V). Wave intensity largely follows the seasonal pattern in the mean wind speed with a substantial variability on weekly scales (see below). At Estonian sites the wave heights are large in October–January and reach the annual maxima in late autumn and early winter (December–January). At Nida November is the roughest month. Relatively low values of the monthly mean wave heights at Narva in November–December compared to those in October apparently reflect the frequent presence of sea ice in the entire eastern Gulf of Finland in late autumn (Sooäär and Jaagus, 2007). The calmest months are in late spring and summer. This variation is adequately reproduced in numerical simulations (Jönsson et al., 2003; Suursaar and Kullas, 2009; Paper III). It also resembles a similar cycle of water level in adjacent coastal waters of Finland (Johansson et al., 2001). The two cycles are only shifted by 1–2 months with respect to each other.

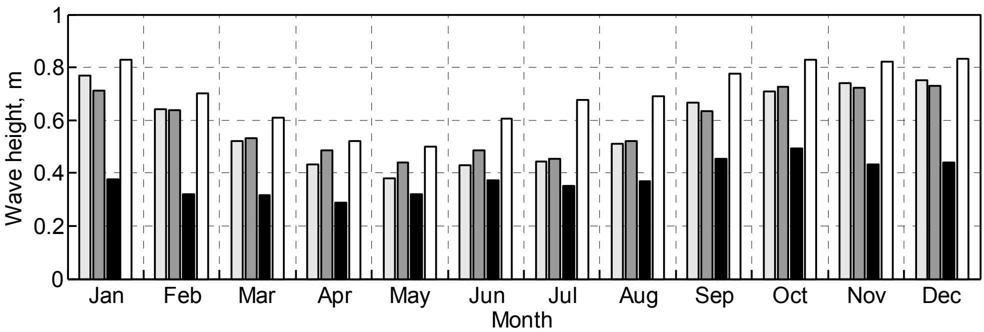

Figure 9. Seasonal variation in the monthly mean wave height at Vilsandi (light grey bars), Pakri (dark grey bars), Narva-Jõesuu (black bars) and Nida (white bars) (Paper V).

The relative amplitude of the variation in the monthly mean wave height is usually clearly larger than a similar variation in the wind speed. For example, at Vilsandi it is ±30–35% of the annual mean: from about 0.39 m (0.40 m in the simulated data) in the calmest months to 0.77 m (0.75 m in the simulated data) in the windiest months (Figure 9). Seasonal variation at the coastal sites is less pronounced than in the offshore; for example, at Almagrundet the mean wave height in the roughest and calmest months differ by 2.2–2.6 times (Broman et al., 2006). The comparatively modest seasonal course is an expected feature of coastal observations. To a large extent it is associated with the frequent presence of weak wave fields even in case of quite strong but offshore winds. This conjecture is supported by the fact that seasonal variations in the wave height at sites reflecting well the properties of open sea waves (such as Vilsandi or Pakri) are clearly more pronounced than the variations in the wind speed. The seasonal cycle is also clearly visible in the most typical wave conditions, dominant wave periods and higher percentiles of observed, measured and hindcast wave heights.

An interesting insight into the quality and representativeness of visual observations can be obtained from the analysis of variations in wave intensity within certain months.

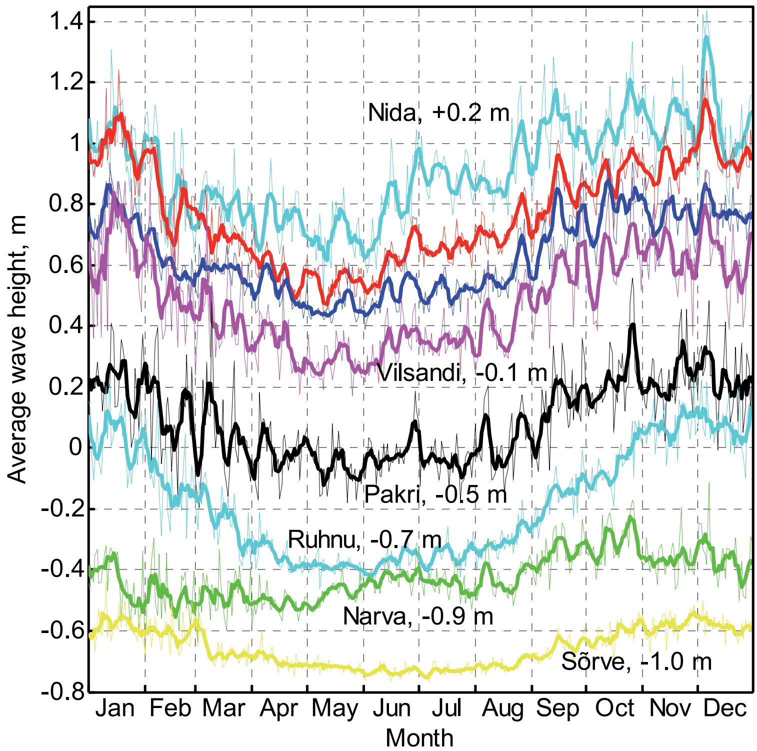

Figure 10. Seasonal variation in the average mean wave height for single calendar days at Nida (cyan, plotted shifted by 0.2 m upwards for better visibility), Liepaja (red), Ventspils (blue), Vilsandi (magenta, –0.1 m), Pakri (black, –0.5 m), Ruhnu (cyan, –0.7 m), Narva-Jõesuu (green, –0.9 m) and Sõrve (yellow, –1.0 m). The records from 29 February are merged with the data from 01 March. The thin lines show the daily average and the bold lines its five-day running average. Based on Figure 4 of Paper IV. From the poster "Lessons from almost seven decades of visual wave observations from the eastern Baltic Sea" by T. Soomere, M. Eelsalu, K. Pindsoo and M. Zujev, presented at the 7th Study Conference on BALTEX, 10–14 June 2013, Borgholm, Sweden.

Figure 10 presents the mean wave height for single calendar days at different observation sites. This quantity eventually contains some noise, the level of which is the largest for the seasons when a relatively small number of measurements exist (Paper II). An important message from such a representation of the wave climate is that several transitional months (such as March or September) host quite large gradients in the long-term wave height. Therefore, the relevant monthly mean wave heights should be used with care in applications. A reasonable alternative is to use the climatologically valid values for single calendar days, for example, to fill gaps in the data (Paper IV). This approach is used several times in Chapter 3.

Another key message from the described coherence of the daily means of the wave heights recorded at different sites is that visual observations, notwithstanding a low accuracy of single recordings, in the long run adequately reflect not only long-term wave statistics but are also able to indicate some potential changes in the wave regime.

3. Decadal and long-term changes

3.1. Introduction

Long-term changes in wind properties and storm activity over the Baltic Sea exhibit greatly variable patterns (Jaagus et al., 2008). The average wind speed over most of the Baltic basin (especially in its southern part) increases (Pryor and Barthelmie, 2003, 2010). Simultaneously, the wind speed has decreased in a part of the Western Estonian Archipelago and on the southern coast of the Gulf of Finland (Keevallik and Soomere, 2004; Kull, 2005). On the one hand, according to some studies, storminess in the entire region gradually decreased over the first half of the 20th century but rapidly increased in the 1980s–1990s (Alexandersson et al., 1998). On the other hand, both the overall storminess and the number of storm days in the Finnish marine areas have decreased since the mid-1990s (Alexandersson et al., 2000; Helminen, 2006).

As discussed above, changes in wave properties in water bodies adjacent to the Baltic Sea also reveal controversial patterns. Early studies identified an increase in the mean wave height over the whole of the North Atlantic and North Sea since about 1950 (Bacon and Carter, 1991; 1993; Kushnir et al., 1997). Contrariwise, WASA Group (1998) concluded that the North Atlantic wave climate has undergone significant decadal variations but revealed no clear trends. An apparent worsening of the storm climate in data-sparse areas was evidently an artefact (Günther et al., 1998). Wang and Swail (2002) argued that the north-eastern Atlantic has roughened in winters of the last four decades. The number of rough wave conditions actually increased only in the 1960s–1970s but both the intensity and duration of severe storms have decreased in the 1990s (Weisse and Günther, 2007).

The described overall match of the shape and basic properties of the observed, measured and modelled properties of the waves in the nearshore suggests that the visually observed data sets properly reproduce the long-term statistics of wave fields in the nearshore of the eastern Baltic Sea coast even if single observations contain considerable errors. These visually observed data sets are particularly significant in the light of the well-known high anisotropy of the Baltic Sea wave fields (Jönsson et al., 2003; Soomere, 2003; Augustin, 2005; Broman et al., 2006; Schmager et al., 2008). The results of several numerical simulations confirm that the areas with the largest average wave intensity are located in the south-eastern and north-eastern regions of the Baltic Proper (Jönsson et al., 2003; Schmager et al., 2008). These areas host high mean wind speeds and correspond to long fetches. Waves may be extremely high also offshore the coasts of Latvia and Saaremaa (Jönsson et al., 2003; Soomere et al., 2008). Several related characteristics such as hydrodynamic bottom stress and resuspension patterns are strongly correlated with these features of the wave climate (Elken et al., 2002; Jönsson et al., 2005). As the distance between the discussed observation sites is much smaller than the extension of the Baltic Proper, the data from such a dense observation network have great potential for validating spatial variations in wave climate changes that have been identified in numerical simulations (Soomere and Räämet, 2011).

Long-term variations in the annual mean wave height (called wave activity for simplicity) are addressed in Papers I, II, IV and V based on observations made at Estonian and Lithuanian sites. These studies were continued during the writing of this thesis by colleagues in the Wave Engineering Laboratory using data from Latvian observation sites (Pindsoo et al., 2012) and unpublished, recently digitized data from the Gulf of Riga (see the reference in the caption to Figure 10). Although single pieces of information about spatial variability of wave activity have been obtained over years by various studies, I present below the whole picture as it is understood today.

3.2. Coherence of interannual variations in the significant wave height

All time series of the annual mean wave heights calculated from visual observations at the coasts of the Baltic Proper and the Gulf of Finland show a reasonable match of years of relatively high and low wave intensity in 1957–1986 (Figure 11). A high correlation (statistically significant at a >99% level) is seen between annual mean wave heights at all Estonian sites within this time interval (Table 3). Therefore, the short-term interannual variability (at time scales of 1–3 years) had the same appearance along the entire eastern Baltic Sea coast from the Curonian Spit to Narva Bay in these years. Especially the match of the data set from the coasts of the Baltic Proper once more confirms that visual wave observations do reflect the basic features of changes to the wave heights.

This coherence ends abruptly starting from the year 1988 (Figure 11, Table 3). From the 1980s onwards, years with relatively high wave intensity at Vilsandi correspond to relatively calm years in Narva Bay. The correlation between the time series for Vilsandi and Narva-Jõesuu is negative for 1987–2008 and the *p*-value suggests that there is no statistically significant correlation indeed. Moreover, the annual mean wave height at Narva-Jõesuu is even in anti-phase with the height in the Baltic Proper. A similar loss of correlation also occurs in the observed and numerically simulated time series of the annual mean wave heights (Paper IV). The coherence, however, continues along the coast of the Baltic Proper. Unfortunately no data from Pakri are available from 1986 onwards.

The adequacy of the described short-term variations and of the level of correlation between the wave intensity at different locations can be to some extent checked by replacing the gaps in the observed data by climatological values of wave height for single calendar days (Section 2.5, Paper IV). Doing so considerably improves the correlation between the observed and simulated wave data but does not alter the correlation of interannual variations until the end of the 1980s and the loss of coherence since then.

The pattern of changes in Figure 11 reveals drastic decadal-scale fluctuations in wave activity in the Baltic Proper during the 1990s and 2000s but a gradual decrease in the annual mean wave height (0.4% per annum) at Narva-Jõesuu. This feature indicates that certain large-scale changes in wind properties over the Baltic Sea have occurred since the mid-1980s. Intriguingly, these changes have taken place on the background of gradually increasing wind speeds in the Baltic Proper (Pryor and Barthelmie, 2003, 2010; Broman et al., 2006). They have mostly affected the proportion or strength of winds that predominantly created waves in the eastern Gulf of Finland. Kull (2005) and Jaagus (2009) demonstrate that during the last 40 years the frequency of south-western winds increased significantly at the "expense" of other wind directions over Estonia. These winds have very limited fetch for waves observed at Narva-Jõesuu. This change thus explains well why the annual mean wave heights have been almost constant or even decreased in Narva Bay.

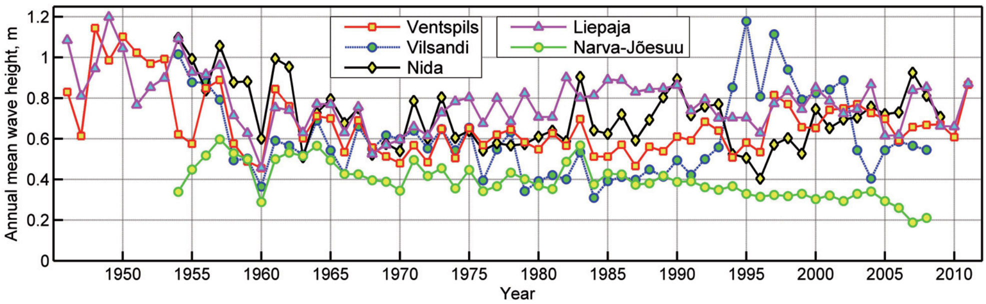

Figure 11. Long-term variations in wave heights at Narva-Jõesuu, Vilsandi, Ventspils, Liepaja and Nida. Data for Ventspils and Liepaja are from Pindsoo et al. (2012) and Soomere (2013).

Table 3. Correlation coefficients (upper right cells) and the statistical significance (*p*-values, lower left cells, in italics) between the annual mean wave heights at Vilsandi, Pakri and Narva-Jõesuu in 1957–2008 (1957–1985 for Pakri). The values in brackets show these quantities for 1957–1986 and 1987–2008 for Vilsandi and Narva-Jõesuu. Years 1954–1956 are omitted (Paper IV).

Site	Vilsandi	Pakri (until 1985)	Narva-Jõesuu
Vilsandi		0.53	–0.14 (0.49/ –0.25)
Pakri (until 1985)	*0.0023*		0.44
Narva-Jõesuu	*0.28 (0.0028/0.47)*	*0.014*	

3.3. Decadal variations in the significant wave height

In the analysis of decadal-scale variations in wave intensity along the eastern Baltic Proper data from Vilsandi (Paper I) were the most controversial. They revealed a quasiperiodic variation in wave activity at decadal scales with an exceptionally large amplitude but with no long-term trend (Figure 11). The interval between subsequent periods of high or low wave activity is about 25 years. The wave heights were relatively large in 1965–1975 and at the end of the 1990s. The increase rate was as high as 2.8% per annum in 1979–1995. Wave activity decreased fast starting from the end of the 1990s. The sea was comparatively calm at the end of the 1950s and in the middle of the 1980s.

Although the fast increase in wave heights at Vilsandi may have partially resulted from a large number of gaps in these years (Figure 3) and/or from the low quality of observations (T. Kõuts, personal communication, 2013), it corresponds to the increase in the annual mean wave height at Almagrundet as well as to the analogous trends for the southern Baltic Sea, North Sea and North Atlantic (Bacon and Carter, 1991; Kushnir et al., 1997; Gulev and Hasse, 1999; Vikebø et al., 2003; Gulev and Grigorieva, 2006; Weisse and Günther, 2007). It also matches the general tendency of the wind speed to increase over the northern Baltic Sea (Broman et al., 2006). Thus, the equally rapid decrease in the wave activity in 1995–2003 was the most controversial, contradicting with a gradual increase in the wind speed at Utö (Figure 12, Paper V) but almost perfectly matching a similar decrease at Almagrundet (Broman et al., 2006).

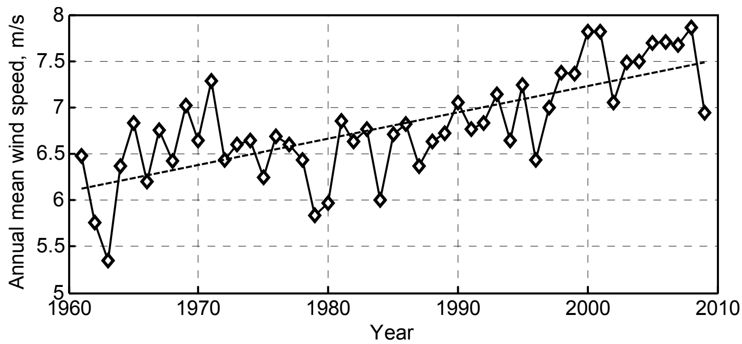

Figure 12. Annual mean wind speed at Utö in 1961–2009. The trendline reveals an increase in the wind speed by 2.84 cm/s/year (Paper V).

Therefore, while the increase in the wave heights generally matches similar trends in the North Sea, both its magnitude and subsequent decrease in the northern Baltic Proper are somewhat counter-intuitive. Moreover, no such variation was recorded along the Lithuanian coast from the observed data (Kelpšaite et al., 2008) and in the middle of the Gulf of Finland from numerical simulations based on high-quality marine winds (Kelpšaite et al., 2009).

As the described changes occurred simultaneously and with a similar relative magnitude at the eastern and western coasts of the Baltic Proper, it is still likely that they reflect the realm of the changing wave situation in particular sea areas rather than failures of instruments or the relay of the observer. The adequacy of these drastic variations in the northern Baltic Proper is questioned against several sources of errors (such as large gaps in the time series or great changes in the duration of ice cover in the vicinity of the observation site) in Papers II and IV.

Paper II presents an analysis of decadal variations in the local wave height at Harilaid in 1966–2006. The time series of significant wave heights were simulated with an SMB model (Section 2.2) using wind information from Vilsandi. The annual means of the observed wave height at Vilsandi and the modelled wave heights at Harilaid were highly correlated but the match of their long-term variations (cf. Figure 11) was far from perfect. A certain mismatch is not surprising because in many occasions the wave generation conditions in remote sea areas govern local wave properties at Vilsandi but the SMB model mostly relies on local wind. The modelled data demonstrated the presence of quasi-periodic cycles with a typical duration of 30–40 years, with no distinct trend. The wave intensity was above average roughly from 1980 to 1995 and lower than average from 1970 to 1980 and up to 1995. Increase in the modelled wave heights occurred in 1975–1993, followed by a subsequent decrease since 1998. The modelled data, however, do not show a large increase at the turn of the millennium but the time series of modelled 99%-iles reveals a clear increase. This feature is particularly interesting, because it may be interpreted as evidence of an increase in the wave heights of extreme storms on the background of a decrease in the overall wave activity (Soomere and Healy, 2008).

As described above, variations in the annual mean wave height at Pakri, the closest observation site to Vilsandi, are the most similar to those at Vilsandi (Figure 11, Paper II). The largest difference is in the data from the first three years of visual observations (1954–1956). The reason for this difference remains unclear in Paper II and is discussed further below. Still, these years were omitted from the correlation analysis in Paper IV (Table 2). There is an increase in the mean wave height at Vilsandi and for a few years at Pakri and Harilaid around the year 1960, and an overall slow decrease until the mid-1970s. As the Pakri data are available only until 1985, it is not possible to establish whether the above drastic variations have extended also to the Gulf of Finland.

A clear decreasing trend in wave activity is evident in the Narva-Jõesuu data. This trend may be related to an asymmetric decrease in the length of the ice season in the Gulf of Finland, which has mostly occurred during a relatively calm season (Sooäär and Jaagus, 2007). Another reason is a substantial increase in the frequency of south-western winds over Estonia (Kull, 2005; Jaagus, 2009). This turn in wind directions means that the frequency of winds corresponding to very short fetches has considerably increased at Narva-Jõesuu. The related changes in the wave field are more clearly visible in the long-term course of the highest waves: the 99%-iles have considerably decreased along the Estonian coast (Suursaar, 2010) but have increased in the north-eastern region of the Gulf of Finland (Soomere et al., 2010).

The data calculated with the WAM model forced by geostrophic winds (Section 2.2) show no statistically significant trend of any of the percentiles (Räämet, 2010). A very slight increase is recorded in the 95%-ile and a similar slight decrease in the

99%-ile at Pakri and Narva-Jõesuu. A very small increase occurs in both values simulated by the WAM model at Vilsandi.

Paper V extends the analysis of the visually observed wave data to the south-eastern part of the Baltic Sea. Basically confirming the results obtained in Kelpšaite et al. (2008), the analysis (that now covers many decades) presents new evidence of large spatial variations in wave properties along the eastern coast of the Baltic Sea. The pattern of large decadal changes in the wave heights is particularly interesting.

A suprising difference exists in the long-term behaviour of the wave height in the southern and northern parts of the Baltic Proper (Figure 11). The temporal courses in wave activity at the Lithuanian sites and Vilsandi match each other relatively well until about 1993. Further on the annual mean wave height behaves completely differently at these sites. The wave height decreases substantially at Nida in 1990–1995 but a gradual increase starts in about 1996. This behaviour is even more surprising when compared with changes in the wind speed (that has gradually increased in the northern Baltic Proper since the 1960s, Figure 12).

As discussed above and in Paper I, the observations at Vilsandi in 1991–2004 include large gaps. The course of wave intensity at all observation sites is re-analysed in Paper IV using the time series in which the missing observations of wave heights have been replaced by their climatological values for the same calendar day (Section 2.5, Paper IV). The two estimates for the annual mean wave heights differ insignificantly for Pakri and Narva-Jõesuu (Figure 13). A relatively large difference is recorded for Narva-Jõesuu starting from 2005. Interestingly, the original and corrected values for Vilsandi almost exactly coincide for these years.

The climatologically corrected values of the annual mean wave height for Vilsandi differ by up to 30% from the values based on original data. The corrected wave intensity is larger for the years with a relatively low wave intensity and long ice cover (for example, in the 1970s). The corrected mean wave heights are reduced by up to 20% in the mid-1990s and at the turn of the millennium when the original data showed extremely stormy years. The increase in wave intensity at the beginning of the 1990s according to the corrected data set is smoother than in the original data. There is still evidence of a substantial increase in the wave heights in 1993–2002 compared with the long-term mean.

The climatologically corrected data sets reveal a much higher correlation with the simulated wave intensity until 1987 than the original time series (Paper IV). This is not unexpected, because the presence of ice is ignored in the simulations but filling the gaps mirrors the ignoring of the ice cover. The correlation between the simulated and observed values of the annual mean wave heights is still completely lost for the years 1988–2007 (Paper IV).

Stormy seasons and periods with ice cover may occur during quite different months in different years (Sooäär and Jaagus, 2007). Therefore the above comparisons based on calendar years may give a somewhat distorted reflection of the severity of wave conditions in a particular autumn-winter windy season. In

Paper IV we analysed the temporal evolution of the average wave height over periods covering the entire windy season (September–March).

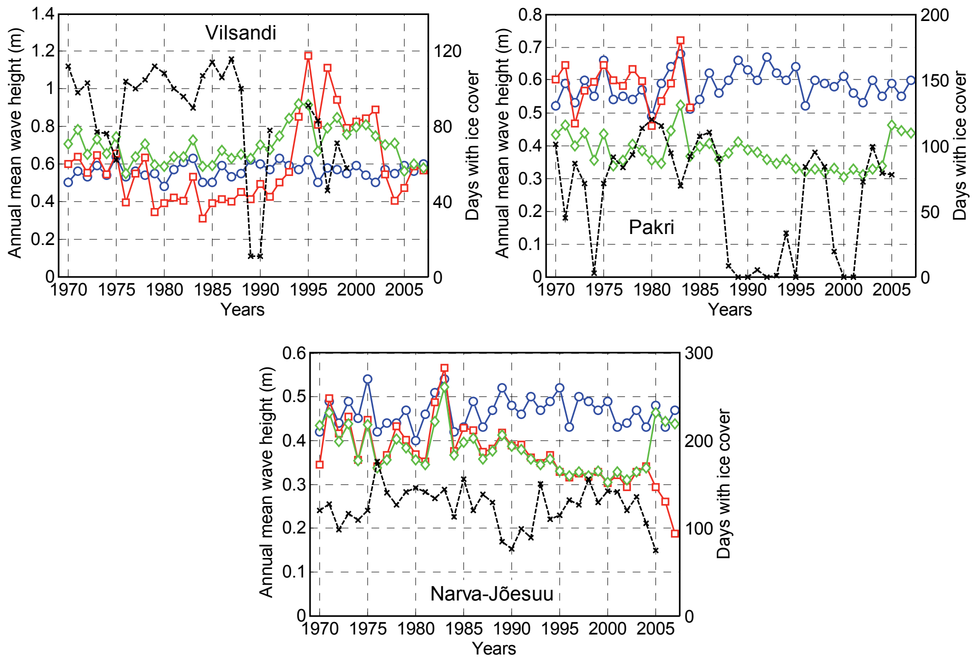

Figure 13. Long-term variations in wave and ice conditions calculated based on calendar years at Vilsandi, Pakri and Narva-Jõesuu. The original observed time series is shown by red squares, climatologically corrected time series by green diamonds, numerically simulated time series by blue circles and the duration of ice coverage (estimated as the number of days from the first appearance of ice to total disappearance of ice) by crosses (Paper IV).

The resulting courses of the observed and measured wave heights, including their interannual, decadal and long-term variations at all sites, are practically the same as presented in Figure 13. There is high interannual variation around the year 1960 in all data sets, a period of relatively low wave intensity in the 1980s and a drastic increase in wave heights over the 1990s at Vilsandi. The correlations between numerically simulated and observed data are also almost the same.

3.4. Long-term changes in wave heights and directions

The presented analysis has revealed several interesting properties of the Baltic Sea wave climate on a decadal scale. Both the visually observed data and numerical simulations clearly demonstrate that the wave activity at the eastern coast of the Baltic Sea has no any clearly defined long-term trend. The longest subtrends persist for about three or four decades. The major feature of the wave climate is the presence of extensive decadal-scale, mostly aperiodic variations at almost all observation sites (Figure 11). The amplitude of these variations is remarkable: the annual mean wave height may change by a factor of two at sites open to the Baltic Proper. The only exception is Narva-Jõesuu where the wave intensity has an overall decreasing trend over half a century.

A recent reconstruction of the long-term course of wave intensity back to the 1940s (Soomere, 2013) together with wave data from the Lithuanian sites (Paper V) sheds more light to changes in the study area. First of all, it clarifies the nature of relatively strong oscillations of wave activity in the mid-1950s and presents evidence that these should be interpreted, as hypothesized in Paper V, as parts of a long decreasing phase in wave intensity from the mid-1940s until about 1970.

This decrease seems to be present along the entire eastern coast of the Baltic Sea. As no existing wave simulations cover such a long time span, the validity of this conclusion needs further analysis. Such an ultimate decrease, by almost a factor of two on average, in wave intensity over three decades is consistent with a substantial decrease in the storminess over these decades in the entire Baltic during the first half of the 20th century (cf. Alexandersson et al., 2000), expressed also as a decrease in the number of storm days in the Baltic region (Bergström et al., 2001). Although the magnitude of the decrease may be somewhat overestimated by observers, the presented data very likely represent a major modification of the Baltic Sea wave fields in the third quarter of the 20th century. The described feature also shows the above-discussed large difference of the wave intensity at Nida and Vilsandi during the first three years of visual observations (1954–1956) in a new light. It is likely that the difference indicates some actual changes in wave activity rather than a systematic overestimation of wave heights at Vilsandi during the first years of the observations.

Numerical simulations suggest that wave intensity did not undergo long-term changes along most of the eastern coast of the Baltic Proper in 1970–2007 (Soomere and Räämet, 2011). Only the north-western coast of Latvia was shown to host an increase. The observed wave data from Ventspils and Liepaja (Figure 11) reveal that such a trend does exist in this area and has a magnitude similar to the numerically simulated one (Pindsoo et al., 2012). Remarkably, this trend started exactly in the year 1970, whereas an even more rapid decrease in the wave height occurred at these sites in the 1950s and the 1960s.

The course of wave intensity had quite a different nature during the fourth quarter of the 20th century and around the turn of the millennium. Numerical simulations suggest that the latter time interval is characterized by a complicated spatial pattern of decadal variations of substantial amplitude (Soomere and Räämet, 2013). Visually observed wave data confirm this hypothesis. While the overall wave intensity in the entire Baltic Sea basin has experienced no considerable changes since the 1970s, the local wave climate has undergone significant changes as discussed in the previous section. For example, wave intensity increased markedly in the northern Baltic Proper during the 1990s. Changes with a comparable (but slightly smaller) amplitude evidently occurred in the south-eastern and south-western parts of the sea. The long-term course of the observed wave heights suggests that these variations in wave activity were a short-term phenomenon. It is likely that the Baltic Sea is now in a phase characterized by relatively moderate average wave heights.

The discussed extensive variations in the wave height in the 1990s can be explained by a concentration of a large part of the centres of cyclones crossing the Baltic Sea in the middle of the Sea of Bothnia. This process is highlighted, for example, as a dramatic increase in the number of days with low pressure at Härnösand in the 1990s (Bärring and von Storch, 2004; BACC, 2008).

The changes before the year 1970 are highly coherent along a more than 500 km long coastal section. It is thus likely that they have been caused by some larger-scale phenomenon. Most of the reconstructions of wind speed over the Baltic for this period reveal some increase in wind intensity rather than decrease (e.g., Pryor and Barthelmie, 2003, 2010; Lehmann et al., 2011). As the Baltic Sea has a strongly elongated shape, a considerable increase or decrease in the wave height may be caused, for example, by a systematic rotation of the predominant direction of strong winds. Such a seeming rotation of the wind rose at a single observation site may be caused by a variation in the trajectory of cyclones. For an observer this process is reflected as a change in wave approach directions.

Similarly to wave periods, the wave propagation direction is often dynamically insignificant but becomes decisive in many applications such as navigation (Bitner-Gregersen et al., 2013) or coastal engineering (Dean and Dalrymple, 2002). The pool of observed data about wave periods and propagation directions is much smaller than that about wave heights.

The predominant wave directions at the observation sites match the directional structure of the prevailing winds and the geometry of the nearshore of the observation sites. The annual distributions of wave approach directions show a certain interannual and decadal variability at most sites but usually reveal no substantial long-term changes (Figure 14). Relatively small changes (but still strongly affecting the course of coastal processes) have been identified at the Lithuanian coast for the years 1993–2008 (Kelpšaite et al., 2011). Several abrupt shifts in the wave approach direction stem from changes in observation conditions (Paper V).

Drastic changes in wave approach directions have occurred at Narva-Jõesuu (Figure 14). Waves mostly approached from the west or north-west until about 1965. The approach direction shifted almost to the north by the 1970s, turned to the south-west over the 1980s and has mostly been from the south within the last two decades. The most frequent propagation direction has rotated by more than 90º. The second most frequent wave direction (south-south-east) has turned in a similar manner. Interestingly, none of these changes are reflected in the simulated propagation directions (Paper IV).

The reasons for the described changes are unclear. The number of sensible wave direction recordings is usually smaller than that of wave heights. Consequently, the reliability of the directional analysis is much lower than that of wave heights. The observers also tend to overestimate the role of relatively short waves (Orlenko et al., 1984). This feature may lead to a certain overestimation of the frequency of locally generated wave fields and may simply highlight changes in the frequency or strength of the local breeze.

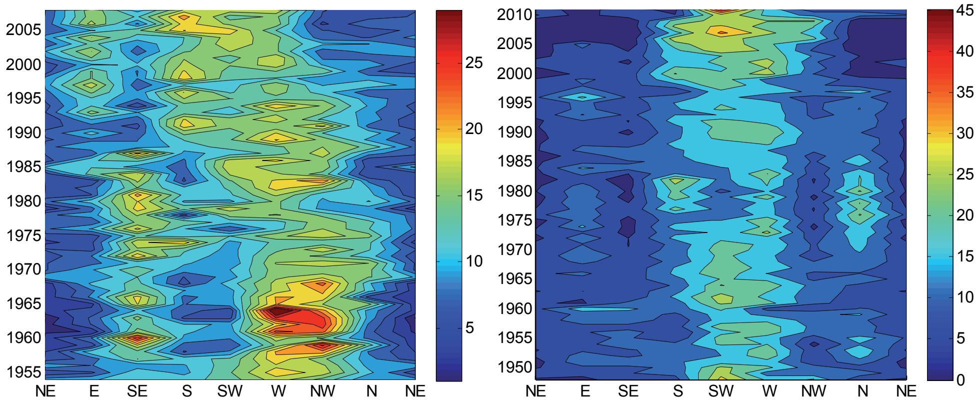

Figure 14. The observed directional distribution of wave approach at Narva-Jõesuu (left panel, 1954–2008, Paper III) and at Liepaja (right panel, 1946–2011, from the poster "Interannual, decadal and long-term variations in the wave fields at the Latvian coast of the Baltic Proper" by K. Pindsoo and T. Soomere, presented at the 11th Colloquium on Baltic Sea Marine Geology, Helsinki–Stockholm, 19–21 September 2012). The colour scale shows the frequency of occurrence (%) of waves from a particular direction.

Still, several arguments suggest that the turn in question reflects certain important changes in wave fields. The turn evolves gradually over many years and is evidently not related to potential inhomogeneities stemming, for example, from the change of observers. More importantly, it matches the increase in the frequency of south-western winds in Estonia at the expense of almost all other wind directions (Kull, 2005; Jaagus, 2009).

The wave period is often considered as a secondary parameter of wave fields, which has less dynamic or kinematic significance and the systematic changes in which are not easy to interpret. This property is, however, important in many aspects of offshore and coastal engineering, for instance, in coastal processes (for example, in terms of the parameters of the width of the equilibrium coastal profile; Dean and Dalrymple, 2002), navigation safety (where the wave steepness is a decisive factor) or renewable energy issues (where it contributes to the available wave energy flux through the group speed, Cruz, 2008). Potential changes in the periods have been addressed in numerical simulations (Räämet, 2010). The largest periods mostly occur in the eastern part of the Baltic Proper and the Bothnian Sea; yet the overall values are largest in the southern Baltic Proper. The numerically simulated changes in wave periods follow the pattern of changes in wave heights. Wave periods have become longer in the eastern part and shorter in the western part of the Baltic Proper. The magnitude of these changes is quite small, maximally a couple of tenths of seconds and can thus be neglected in practical applications.

3.5. Wave properties and ice cover

One of the key features forming the Baltic Sea wave fields is the ice cover. The maximum area covered by ice in the Baltic Sea varies largely between different years (Bergström et al., 2001; Leppäranta and Myrberg, 2009). The duration of the ice cover, for example at Vilsandi, may vary from a few to more than 100 days during a winter (Figure 13). The presence of ice may have twofold impact on the observed wave data. Fast ice often makes visual wave observations impossible. An ice cover upwind from the observation site reduces the effective fetch length and modifies the wave properties.

The absence of sea and coastal ice in some years generally leads to enhanced erosion of coastal areas of seasonally ice-covered seas (Overeem et al., 2011; St-Hilaire-Gravel et al., 2012). Changes in ice conditions evidently play a great role in the intensity of coastal processes in the Baltic Sea area (Orviku et al., 2003). A combination of occasional strong wave storms, high surges and sediment deficiency at the Baltic Sea coasts makes this area extremely vulnerable to any changes in hydrodynamics (Eberhards and Lapinskis, 2008; Kartau et al., 2011). The most dramatic erosion events have been shown to occur when late autumn and winter storms attack coastal sections that in more severe winters would be protected by ice cover (Ryabchuk et al., 2011).

A common opinion is that climate changes in the Baltic Sea area will generally lead to a shortening of the ice period (BACC, 2008). This means an increase in the total wave energy levels that reach the nearshore and the coast. Changes in the wave climate even in terms of shifts in the stormy season to months with no ice cover may lead to most severe destruction of vulnerable beaches in the eastern Baltic Sea (Orviku et al., 2003; Ryabchuk et al., 2011).

The average number of days with ice has decreased steeply along the entire coast of Estonia (Jaagus, 2006; Sooäär and Jaagus, 2007). The ice covered parts of the coasts of Estonia from mid-November to mid-April in the past. The changes in the beginning and end of the ice season have been almost symmetric, with a slightly larger number of additional ice-free days in spring (Sooäär and Jaagus, 2007). The impact of the gradual lengthening of the ice-free season is not straightforward. December, which is mostly ice-free nowadays, is one of the windiest months and April, which is also largely ice-free now at Vilsandi, is one of the calmest months (Section 2.5). If the season of the highest waves overlaps with the ice season (e.g., in the eastern part of the Gulf of Finland where fast ice is frequently formed in November), the reduction of the ice season may drastically intensify the coastal processes (Ryabchuk et al., 2011). Such an effect becomes evident in Paper IV where the inserting of climatological values for the missing measurements (this operation has basically the same effect as partially ignoring the ice) results in a clear increase in the annual mean wave height at Vilsandi in normal and relatively severe winters of 1975–1988 (Figure 13).

Although the lengthening of the ice-free period obviously increases the total wave load on the coasts, its impact on the average wave properties is not straightforward. Typically, Estonian coastal waters are ice-covered from January to March (Sooäär and Jaagus, 2007). Figure 9 and Figure 10 suggest that the absence of ice cover in the windiest months such as December or January would generally cause an increase in the annual mean wave height at Vilsandi and Pakri, but the absence of ice cover in March–April may lead to its decrease. The construction of adequate wave statistics for seasonally ice-covered seas is extremely complicated (Kahma et al., 2003; Tuomi et al., 2011). Moreover, most of the rapid changes to the coast occur during a few severe wave storms (Orviku et al., 2003). The presence or absence of ice during these storms only weakly affects the annual mean wave height.

Somewhat surprisingly, the analysis in Paper IV shows virtually no correlation between the annual mean wave height and the length of the ice cover at the Estonian observation sites (Figure 13). The same feature is revealed for the average wave heights calculated for windy seasons and estimated with the use of climatologically corrected daily values. Although there is some qualitative match of these quantities in single years, the relevant correlation coefficients are well below 0.2 and no statistically significant correlation exists.

3.6. Quantifying the impact of ice cover on wave fields

The results presented in Section 3.5 are in some sense not satisfactory. The absence of any correlations between the average of the basic properties of wave fields and ice cover is not constructive as many recent studies have revealed a clear relationship between ice conditions and coastal processes. Several options for identifying a suitable measure for quantifying the impact of ice on wave fields in seasonally ice-covered seas are explored in Paper VI. The aim is to identify a more appropriate but still simple measure of wave fields that would be able to reflect the potential impact of the change in the duration of the ice season.

As the "linear" measures such as the annual average wave height were unable to do the job (Paper IV), it is natural to use some quadratic (second-order) measures such as the wave energy or wave energy flux (called also wave power). The latter quantity is commonly recognized as an acceptable measure of the instantaneous intensity of wave-driven alongshore sediment drift (USACE, 2002). Other measures that may have the potential of quantifying the role of ice in the coastal processes are the mean energy and the mean wave height over the ice-free season. All these quantities are calculated for time periods from July of a selected year until June of the subsequent year. Differently from the analysis in previous sections, here the mean energy and the mean wave height are evaluated for the ice-free period. The total wave energy flux reaching the coast during the ice-free period is called bulk wave power below.

The analysis is based on the wave properties derived from visual observations during 1954–2005 at three observation sites at the Estonian coast (Narva-Jõesuu, Pakri (until 1985) and Vilsandi) and on the output of numerical simulations using the wave model WAM (Komen et al., 1994; Section 2.2) for 1970–2005.

The wave data are amended with the data on the duration of the ice season for these sites. Observations of ice properties in the nearshore zone of Estonia started at several lighthouses in the 1800s. They have been performed systematically at several locations by the Estonian Meteorological and Hydrological Institute since the mid-20th century. The ice data include the dates of the first freezing, the formation of permanent ice cover, the end of permanent ice cover and the final disappearance of the ice and, optionally, the thickness of the ice cover (Jevrejeva and Leppäranta, 2002). The date of the first freezing (the first appearance of sea ice) is registered when ice of any type is first observed (Sooäär and Jaagus, 2007).

The duration of the ice season is estimated in Paper VI for each site and winter as the number of days, from July to June of the subsequent year, between the day of the first appearance of the ice cover and that of the total disappearance of the ice. Similar to historical visual wave observations, ice observations have extensive gaps and uncertainties. Since wave observations were made for areas located at some distance from the shore, they were at times performed in the presence of ice phenomena. As a result, on many occasions quite high waves have been recorded within the formal ice season as defined above. Such events are ignored in the calculations in Paper VI based on the following assumptions: (1) the first appearance of the ice is associated with the freezing of onshore ground in potential areas of coastal erosion; (2) these potentially erodible coastal sediments are frozen until the ice has completely disappeared.

As wave periods were available only for a part of the visually observed data, the wave energy flux was calculated using the approximation of long waves. Doing so is generally adequate for visually observed waves but may to some extent overestimate the wave energy flux for numerically simulated waves (for which the water depth at the relevant model grid cells was larger than in the observation area) and also for waves observed at Pakri. This bias, however, evidently does not affect the correlation between the resulting estimates and the parameters of the ice season. The missing data in visual observations were replaced by their climatological values for each calendar day as described in Section 2.5.

Similarly to the duration of the ice season (Sooäär and Jaagus, 2007; Paper VI), all three parameters of wave fields exhibit quite large variations in single years. The standard deviation of single annual values from the long-term mean is typically 40–50% for the observed and 20–30% for the modelled wave properties.

The observed average wave height over the ice-free period has no correlation with the length of the ice-free season. On the contrary, the similar modelled wave height showed a high negative correlation (statistically significant at the 95% confidence level) with the duration of the ice season at Vilsandi and Narva-Jõesuu.

The modelled mean wave energy over the ice-free period reveals a significant negative correlation with the duration of the ice season only at Narva-Jõesuu and

Pakri. Somewhat surprisingly, the similar observed quantity has a significant positive correlation with the duration of the ice season at Narva-Jõesuu.

No statistically significant correlation between the mean wave energy and the duration of the ice season exists for the two other sites. This feature is not surprising for both data sets at Vilsandi and Pakri because the mean wave energy only implicitly reflects variations in the duration of ice cover. The discrepancy at Narva-Jõesuu may reflect insufficient temporal resolution of visual observations that are often only possible once a day during the windiest season just before ice formation. However, it once more signifies that the outcome of single visual wave observations should be interpreted with great care.

The bulk wave power provides the best performance in this respect. Its short-term interannual variations are in counter-phase with the duration of the ice cover (Figure 15). It is natural that long ice-free autumns correspond to large annual values of this measure, while long ice seasons correspond to its relatively low levels. The numerically simulated data from all sites reveal a statistically significant negative correlation at a >95% confidence level between the duration of the ice season and the bulk wave power. There is, however, virtually no correlation between the bulk wave power estimated from visual observations and the duration of the ice season at Pakri and Narva-Jõesuu.

The key finding in Paper VI is that the commonly used characteristics of wave fields such as the mean wave energy and the bulk wave power, even if calculated over the ice-free time, are not necessarily strongly correlated with the duration of the ice season at the coasts of the north-eastern Baltic Sea. Contrariwise, such correlations are highly dependent on the particular site. This feature should be carefully accounted for in the estimates of the impact of potential climate warming on the intensity of coastal processes. Namely, the above-discussed obvious convenient measures for wave-driven impact on the coast may be completely uncorrelated with changes in ice conditions. A possible reason is that the duration of the ice season and the wave intensity may have complicated interrelations depending on the openness of a particular site to the waves excited by predominant winds.

Finally I would like to note that the research in Paper VI focuses on a single ice-driven limitation of the impact of waves on coastal processes and omits several indirect but still equally important effects of coastal ice. Firstly, virtually all properties of ice have been ignored and the analysis exclusively relies on the duration of the ice period. In many instances, extensive ice-driven erosion and ice ride-up on the coast may mobilize sediments or destroy dune vegetation (Leppäranta, 2013). Somewhat less visible processes are bottom scouring and transport of large boulders. These effects usually occur irregularly. Although they are definitely caused by specific wind conditions, there seems to be no way to relate them to wave activity (except for specific cases when thin coastal ice is destroyed and piled up on a coast by a strong late autumn storm). The additional forces that wave-driven mass and momentum transport exert to the ice edge are often decisive for ice formation and destruction but are negligible compared to the wind impact over the entire ice sheet in terms of ice drift.

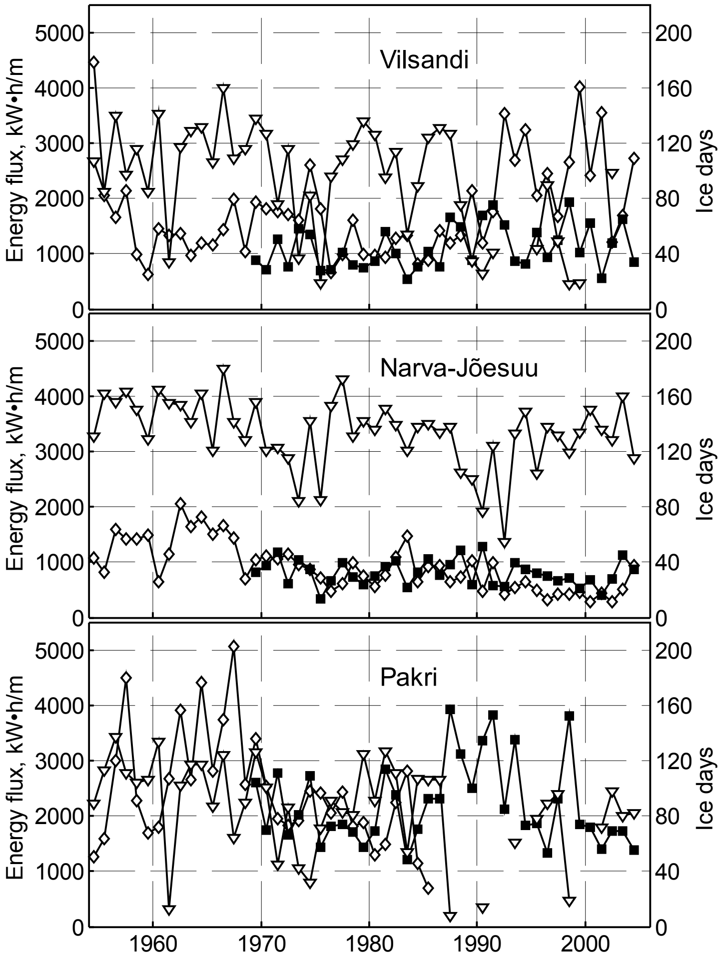

Figure 15. Long-term variations in the total energy flux during the ice-free season and the ice season duration (triangles) at Vilsandi, Narva-Jõesuu and Pakri calculated over the time period from 1 July to 30 June of the subsequent year. Diamonds and squares indicate the estimates of the energy flux derived from wave observations and simulated data, respectively (Paper VI).

Conclusions

Summary of the results

The main aim of this thesis was to reconstruct the basic features of the wind wave climate and its possible decadal and long-term variations for the eastern Baltic Proper and the Gulf of Finland by using historical visual observations of wave properties. The focus was on the coastal waters of Estonia. The key properties of the nearshore wave climate in the areas in question were determined from records at eight coastal measurement sites in (1946)1954–2008(2011) in terms of the typical and extreme wave heights, wave periods and approach directions and in terms of the distribution of the listed properties. The results were interpreted in the light of simulations with a fetch-based wave model and reconstructions of the wave climate using a contemporary spectral wave model WAM.

While the accuracy of single observations is not particularly high and the recorded time series may contain considerable uncertainties, statistical distributions of various wave properties reasonably match the similar distributions obtained from instrumental measurements and numerical simulations. The pattern of seasonal, annual, interannual and decadal-scale variations is mostly reliable. The monthly mean wave height follows the seasonal variation in wind speed with a maximum in October–January at Estonian coastal sites and in November at the Lithuanian coast with the late spring and early summer months being the calmest. The directional distributions of waves match the directional structure of the prevailing winds in the area.

Owing to the extremely complex geometry and bathymetry of the Baltic Sea, it is often almost impossible to reconstruct the offshore wave properties from those observed near the coast. It is, however, possible to identify *changes* in wave properties at different sites and in this way to recognize changes in wave generation conditions and to some extent spatio-temporal variations in these changes. Although the observed wave properties are site-specific, the key contribution of this work is the detection of a new and partially unexpected picture of changes in wave activity in space and time. As the used data characterize the eastern (downwind) parts of the Baltic Sea, the results also reflect certain changes in the climate of the entire Baltic Sea basin.

The long-term course of the wave heights in the study area consists of two phases. Wave activity generally decreased from the beginning of the observations (1940s–1950s) until about the year 1970 in the entire study area. Its further behaviour had mostly a quasiperiodic nature, with the interval between subsequent periods of high or low wave activity about 25 years and strong differences between the southern and northern parts of the sea. The northern Baltic Proper experienced a rapid increase in the annual mean wave height from the mid-1980s to the mid-1990s and a drastic decrease since about 1997. The average wave height was at its lowest in the 1990s in the south-eastern Baltic Proper.

An interesting outcome is an abrupt change in the match of the long-term course in the annual mean wave height in different coastal sections. This quantity revealed nearly synchronous interannual variations over the entire eastern Baltic Proper coast from the 1950s until the mid-1980s. Starting from the end of the 1980s, the temporal course of wave activity in the eastern Gulf of Finland has been essentially decoupled from that in the northern Baltic Proper.

Although there is evidence about gradual increase in the mean wind speed over the Baltic Sea basin, the annual mean wave heights reveal no long-term increase at any of the observation sites. A highly interesting feature is a drastic change in observed wave approach directions at Narva-Jõesuu. The most frequent wave propagation direction has rotated by more than 90º since the end of the 1970s. Notable is also the associated decreasing trend in the 99%-iles of wave heights near the northern Estonian coast, which differs from trends in average wave heights (Soomere et al., 2010; Suursaar, 2010). All these features can be explained by a rotation of the predominant wind directions, possibly caused by changes in the trajectories of cyclones.

Main conclusions proposed to defend

1. The properties of the Baltic Sea wave fields extracted from visual observations are consistent with the existing knowledge: the long-term average significant wave height in the nearshore is 0.7–0.8 m, the wave regime is highly intermittent (maximum wave heights by an order of magnitude exceed the average heights), common wave periods are 2–4 s in the nearshore and 3–6 s offshore, wave approach directions follow the two-peak angular structure of predominant winds and the seasonal course of the wave heights matches the similar course of wind speed.
2. The properties of wave fields in extreme storms in Estonian coastal waters match those extracted from numerical simulations. The highest waves once in about 50 years may reach 6 m (periods 11–12 s) near Vilsandi, 5 m (periods 9–10 s) near Pakri and 4 m (periods 7–8 s) near Narva-Jõesuu.
3. The pattern of interannual variations in the wave height was highly coherent along the eastern Baltic Sea coast from the mid-1950s until the year 1987. Starting from 1988, the years with a relatively large mean height in the Baltic Proper correspond to low wave intensity in the eastern Gulf of Finland.
4. Wave activity decreased in the 1950s–1960s and was at its lowest in the 1970s in the eastern Baltic. Its further decadal variations had completely different courses in different parts of the Baltic Sea. Relatively high wave activity in the northern Baltic Proper in the 1990s was accompanied by low wave heights at the south-eastern coast of the Baltic Sea.
5. The described changes are not consistent with the gradual increase in the annual mean wind speed in the northern Baltic Proper. They have thus been caused by other changes in the wind properties, possibly by a clustering of a

large part of low pressure systems in the Sea of Bothnia in the 1990s (Bärring and von Storch, 2004).

6. No long-term trend in terms of annual mean wave height is present at any of the visual observation sites. Only at Narva-Jõesuu the wave heights have been decreasing since the mid-1960s. This conclusion is consistent with independent estimates of the long-term course of wave heights at the northern coast of Estonia (Suursaar, 2010).
7. A major rotation of the predominant wave approach direction by about 90° since the end of 1970s has been identified at Narva-Jõesuu. This rotation was not replicated in numerical simulations of Räämet (2010) and in other data sets.
8. There is no evident correlation between the commonly used wave characteristics (such as the annual mean wave height or the annual mean energy) and the length of the ice season. A reasonable measure of the impact of ice cover on waves is the annual integral wave energy flux.

Recommendations for further work

As wind waves not only affect offshore activities but are one of the main driving forces of coastal processes, especially for the vulnerable eastern coast of the Baltic Sea, a better understanding of their past, current and future properties is essential for all coastal countries of this region. In particular, possible increase in the frequency and/or severity of marine coastal hazards along with global climate changes or even a change in the typical wave approach direction may considerably alter the conditions of operation and maintenance of the coastal infrastructure and environment.

Estonia as a marine country is using its coastal area in a variety of economic applications such as shipping or recreation. Several cities are low-lying and possibly subject to wave-induced coastal hazards. The Estonian coast is in some places very vulnerable and frequent storm surges and sea level elevations, possibly enhanced by wave action, increase the pressure. Recent studies of extreme conditions (e.g., in November 2001 and January 2005; Soomere, 2005; Soomere et al. 2008a) in the Baltic Sea revealed extensive gaps in our knowledge about the extremes of the wave fields. We have to admit that these gaps have not been filled yet even by means of contemporary wave models (Räämet, 2010).

Along with several interesting and surprising features, the performed analysis revealed a number of shortcomings in our perception of the wave climatology and potential changes in the wave climate. First of all, the presented results indicate that possible changes in wind direction may have a much larger role in the variations in the wave climate than alterations in wind speed. This conjecture, albeit largely expected because of the elongated shape of the Baltic Sea, is still waiting to be verified through numerical simulations (Räämet, 2010). The available set of instrumentally measured wave data is fairly small in the eastern Baltic and of little use for resolving this issue. The peril here is that many Estonian beaches are open to a few directions that not necessarily match the directions of the most frequent or the strongest winds. This peculiarity causes high intermittency of wave fields in the vicinity of many existing and planned coastal engineering structures and suggests that even small changes in the direction of strong winds may lead to substantial changes in the severity of wave conditions in semi-sheltered bays.

The quality of numerically reconstructed wind fields is the narrowest bottleneck here. It is not enough to validate or tune the wind fields against wind data at selected measurement sites. It is necessary to get the wind fields also correct for the open sea areas in terms of their ability to excite high and long waves. Various wave properties are here a very useful tool for assessment of the quality of different wind data sets. Given the existing large biases between the modelled and measured wind data for the Baltic Sea (Ansper and Fortelius, 2003; Keevallik et al., 2010), the use of historical wave data for this purpose has particularly great potential for improving the quality of reconstruction of atmospheric fields in the past. The results are of much value also for adequate modelling of high water levels and patterns of currents.

The analysis above has once more highlighted a number of discrepancies between measured and observed wave data at different sites of the Baltic Sea. Although the differences can be interpreted as reflecting the internal spatio-temporal variability of the Baltic Sea wave climate, the provided arguments are mostly qualitative and quantitative estimates of this variability have quite a large uncertainty. In essence, the reliability and associated potential for the use of visual wave data for quantitative assessment of changes in the offshore wave properties remain questionable. A reasonable way forward seems to be high-resolution evaluation of changes in the properties of waves approaching the observation sites from different directions. A reconstruction of the offshore wave characteristics may be possible for certain directions similarly to the possibilities of reconstructing marine wind fields from coastal stations (Keevallik, 2003b).

It is commonly accepted that changes in certain 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 (Alexandersson et al., 1998; Suursaar et al., 2006), play an important role in the formation of long-term variations in the Baltic Sea wave fields. Importantly, changes in long-term wave statistics can also be used to identify potential changes in the “climate” of forcing factors. Although historical visual observations have low temporal resolution and questionable quality of single recordings, the discussion above has demonstrated that the overall (at least qualitative) variations in the main wave parameters have high potential to reveal such changes in the offshore. Even if it is not always possible to reconstruct the open sea wave properties from the results of nearshore observations, changes in wave generation conditions can eventually be recognized from these data.

Last but not least, in the changing climate conditions one of the key questions would be the possible economic consequences. This analysis is still missing due to limited knowledge about the impact of different hydrometeorological drivers and large uncertainties in the methods of evaluation of the cost of various scenarios.

Bibliography

Alari V., Raudsepp U., Kõuts T. 2008. Wind wave measurements and modelling in Kudema Bay, Estonian Archipelago Sea. *J. Marine Syst.*, 74, Suppl., S30–S40.

Alexandersson H., Schmith T., Iden K., Tuomenvirta H. 1998. Long-term variations of the storm climate over NW Europe. *Global Atm. Ocean System*, 6, 97–120.

Alexandersson H., Tuomenvirta H., Schmith T., Iden K. 2000. Trends of storms in NW Europe derived from an updated pressure data set. *Clim. Res.*, 14, 71–73.

Ansper I., Fortelius C. 2003. Verification of HIRLAM marine wind forecasts in the Baltic. *Publ. Inst. Geogr. Univ. Tartuensis*, 93, 195–204 (in Estonian with English summary).

Augustin J. 2005. *Sea state climate of the Baltic Sea 1958–2002 based on numerical data*. Diploma thesis. Institute for Coastal Research, GKSS Research Center Geesthacht, Germany, 2005 (in German).

Babanin A. V., Hsu T.-W., Roland A., Ou S.-H., Doong D.-J., Kao C. C. 2011. Spectral wave modelling of Typhoon Krosa. *Nat. Hazards Earth Syst. Sci.*, 11, 501–511.

Badulin, S. I., Grigorieva, V. G. 2012. On discriminating swell and wind-driven seas in Voluntary Observing Ship data. *J. Geophys. Res.–Oceans*, 117, Art. No. C00J29.

[BACC] The BACC Author Team 2008. *Assessment of climate change for the Baltic Sea basin*. Reg. Clim. Stud., Springer-Verlag, Berlin, Heidelberg, 473 pp.

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

Bacon S., Carter D.J.T. 1993. A connection between mean wave height and atmospheric pressure gradient in the North Atlantic. *Int. J. Climatol.*, 13, 423–436.

Bergström S., Alexandersson H., Carlsson B., Josefsson W., Karlsson K.-G., Westring, G. 2001. Climate and hydrology of the Baltic Basin. In: Wulff F., Rahm L., Larsson P. (Eds.), *A systems analysis of the Baltic Sea*. Ecological Studies, 148, Springer, Berlin, Heidelberg, 75–112.

Bernhoff H., Sjöstedt E., Leijon M. 2006. Wave energy resources in sheltered sea areas: a case study of the Baltic Sea. *Renew. Energy*, 31 (13), 2164–2170.

Bitner-Gregersen E. M., Eide L. I., Hørte T., Skjong R. 2013. *Ship and offshore structure design in climate change perspective*. SpringerBriefs in Climate Studies. Springer Heidelberg New York Dordrecht London, 69 pp.

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

Booji N., Ris R., Holthuijsen L. 1999. A third generation wave model for coastal regions, 1: model description and validation. *J. Geophys. Res.*, 104, 7649–7666.

Broman B., Hammarklint T., Rannat K., Soomere T., Valdmann A. 2006. Trends and extremes of wave fields in the north-eastern part of the Baltic Proper. *Oceanologia*, 48 (S), 165–184.

Bumke K., Hasse L. 1989. An analysis scheme for determination of true surface winds at sea from ship synoptic wind and pressure observations. *Bound. Lay. Meteor.*, 47, 295–308.

Bärring L., von Storch H. 2004. Scandinavian storminess since about 1800. *Geophys. Res. Lett.*, 31 (20), L20202.

Caires S., Sterl A. 2005. 100-year return value estimates for ocean wind speed and significant wave height from the ERA-40 data. *J. Climate*, 18, 1032–1048.

Cieślikiewicz W., Herman A. 2002. Numerical modelling of waves and currents over the Baltic Sea and the Gulf of Gdansk. In: *Proc. 5th Int. Conf. Hydro-Science and Eng.*, Warsaw, Poland.

Cieślikiewicz W., Paplińska-Swerpel B. 2008. A 44-year hindcast of wind wave fields over the Baltic Sea. *Coast. Eng.*, 55, 894–905.

Cox A.T., Cardone V.J., Swail V.R. 1998. Evaluation of NCEP/NCAR reanalysis project marine surface wind products for a long term North Atlantic wave hindcast. In: *Proc. 5th International Workshop on Wave Hindcasting and Forecasting*, January 26–30, Melbourne, Florida, USA.

Cruz J. 2008. *Ocean wave energy, current status and future perspectives (green energy and technology)*. Springer.

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

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

Dean R. G., Dalrymple R. A. 2002. *Coastal processes with engineering applications*. Cambridge University Press, 475 pp.

Dodet G., Bertin X., Taborda R. 2010. Wave climate variability in the North-East Atlantic Ocean over the last six decades. *Ocean Model.*, 31, 120–131.

Dragani W. C., Martin P. B., Simionato C. G., Campos M. I. 2010. Are wind wave heights increasing in south-eastern South American continental shelf between 32 degrees S and 40 degrees S? *Cont. Shelf Res.*, 30 (5), 481–490.

Druet C., Massel S., Zeidler R. 1972. Statistical characteristics of wind waves in the Baltic coastal zone in the Gulf of Gdansk and open Baltic Sea. *Rozprawy Hydrotechnictne, Zeszyt*, 30, 49–84 (in Polish, cited after Schmager et al., 2008).

DWD 2006. *Seegangsklimatologie der Ostsee (1952 bis 2002)*. Deutscher Wetterdienst, Hamburg.

Eberhards G., Lapinskis J., Saltupe B. 2006. Hurricane Erwin 2005 coastal erosion in Latvia, *Baltica*, 19 (1), 10–19.

Eberhards G., Lapinskis J. 2008. *Processes on the Latvian coast of the Baltic Sea*. Atlas, University of Latvia, Riga.

Elken J., Raudsepp U., Soomere T. 2002. On the current- and wave-induced sediment redistribution patterns in the Gulf of Riga. *Terra Nostra*, 4, 401–406.

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

Geng Q., Sugi M. 2001. Variability of the North Atlantic cyclone activity in winter analyzed from NCEP–NCAR reanalysis data. *J. Climate*, 14, 3863–3873.

Grabemann I., Weisse R. 2008. Climate change impact on extreme wave conditions in the North Sea: an ensemble study. *Ocean Dyn.*, 58, 199–212.

Grigorieva V., Gulev S. 2006. Extreme wind waves worldwide from the VOS data and their changes over the last 50 years. In: *Proc. 9th International Workshop on Wave Hindcasting and Forecasting*, September 24–29, 2006, Victoria, British Columbia, Canada.

[Guidelines] 1985. *Guidelines for Hydrometeorological Stations and Posts. Meteorological observations at stations*. Gidrometeoizdat, Leningrad, 3 (1), 300 pp. (in Russian).

Gulev S. K., Hasse L. 1998. North Atlantic wind waves and wind stress fields from voluntary observing ship data. *J. Phys. Oceanogr.*, 28, 1107–1130.

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

Gulev S. K., Grigorieva V., Sterl A., Woolf D. 2003. Assessment of the reliability of wave observations from voluntary observing ships: insights from the validation of a global wind wave climatology based on voluntary observing ship data. *J. Geophys. Res.*, 108 (C7), 3236.

Gulev S. K., Grigorieva V. 2006. Variability of the winter wind waves and swell in the North Atlantic and North Pacific as revealed by the Voluntary Observing Ship data. *J. Climate*, 19 (21), 5667–5685.

Günther H., Rosenthal W. 1995. *Model documentation of HYPAS*. Institut für Gewässerphysik. Abteilung GMS. GKSS-Forschungszentrum Geesthacht GmbH, Geesthacht, Germany, 20 pp.

Günther H., Rosenthal W., Stawarz M., Carretero J. C., Gomez M., Lozano I., Serano O., Reistad M. 1998. The wave climate of the Northeast Atlantic over the period 1955–1994: the WASA wave hindcast. *Global Atmos. Ocean Syst*., 6, 121–163.

Helminen J. 2006. Finnish local view on the factors accounting for the costs of weather-related disasters (specifically, floods and storms) in recent decades and implications of understanding these for both research and policy. In: Höppe P., Pielke R.Jr. (Eds), *Workshop on Climate Change and Disaster Losses: Understanding and Attributing Trends and Projections*, 25–26 May, Hohenkammer, Germany, 134–144.

Hogben N., Lumb F. E. 1967. *Ocean wave statistics; a statistical survey of wave characteristics estimated usually from Voluntary Observing Ships sailing along* *the shipping routes of the world*. London, H.M.S.O, Ministry of Technology, National Physical Laboratory, 263 pp.

Hogben N., Dacunka N. M. C., Olliver G. F. 1986. *Global wave statistics*. Unvin Brothers, London.

Holliday N. P., Yelland M. J., Pascal R., Swail V. R., Taylor P. K., Griffiths C. R., Kent E. 2006. Were extreme waves in the Rockall Trough the largest ever recorded? *Geophys. Res. Lett.*, 33, L05613.

Huttula T. 1994. Suspended sediment transport in Lake Sakylan Pyhajarvi. *Aqua Fennic*a, 24 (2), 171–185.

Häggmark L., Ivarsson K.-I., Gollvik S., Olofsson P.-O. 2000. MESAN, an operational mesoscale analysis system. *Tellus*, 52A, 2–20.

Hünicke B., Soomere T., Madsen K. S., Johansson M., Suursaar Ü., Zorita E. 2013. Sea level and wind waves. Submitted to: *The BACC II Book*, Springer, to be published in winter 2013/2014.

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

Jaagus J. 2006. Trends in sea ice conditions on the Baltic Sea near the Estonian coast during the period 1949/50–2003/04 and their relationships to large-scale atmospheric circulation. *Boreal Env. Res.*, 11, 169–183.

Jaagus J. 2009. Pikaajalised muutused tuule suundade korduvuses Eesti läänerannikul. *Tallinna Ülikooli Ökoloogia Instituut. Publikatsioonid*, 11, 11–24.

Jaagus J., Post P., Tomingas O. 2008. Changes in storminess on the western coast of Estonia in relation to large-scale atmospheric circulation. *Climate Res.*, 36, 29–40.

Jevrejeva S., Leppäranta M. 2002. Ice conditions along the Estonian coast in a statistical view. *Nordic Hydrol.*, 33 (2/3), 241–262.

Johansson M., Boman H., Kahma K. K., Launiainen J. 2001. Trends in sea level variability in the Baltic Sea. *Boreal Env. Res.*, 6, 159–179.

Jönsson A., Broman B., Rahm L. 2003. Variations in the Baltic Sea wave fields. *Ocean Eng.*, 30 (1), 107–126.

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

Kahma K. 1981. A study of the growth of the wave spectrum with fetch. *J. Phys. Oceanogr*., 11, 1503–1515.

Kahma K., Rantanen E., Saarinen J. 1983. *Wave data from the southern Bothnian Sea 1973–1975, 1981.* Finnish Institute of Marine Research, Internal report 1/1983 (In Finnish with English summary).

Kahma K., Calkoen C. J. 1992. Reconciling discrepancies in the observed growth of wind generated waves. *J. Phys. Oceanogr*., 22, 1389–1405.

Kahma K. K., Pettersson H. 1993. *Wave statistics from the Gulf of Finland. Finish Institute of marine Research*. Internal report 1/1993 (In Finnish with English summary).

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

Kahma K., Pettersson H., Tuomi L. 2003. Scatter diagram wave statistics from the northern Baltic Sea. MERI – *Report Series of the Finnish Institute of Marine Research*, 49, 15–32.

Kalnay E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K. C., Ropelewski C., Wang J., Leetmaa A., Reynolds R., Jenne R., Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, 77 (3), 437–471.

Karppinen T., Ling N. 1998. Estonia: hard facts and realities. *Naval Architect*, September, 9.

Kartau K., Soomere T., Tõnisson H. 2011. Quantification of sediment loss from semi-sheltered beaches: a case study for Valgerand Beach, Pärnu Bay, the Baltic Sea. *J. Coast. Res.*, SI 64, 100–104.

Keevallik S. 2003a. Tuuled Tallinna lahel. *Publicationes Instituti Geographici Universitatis Tartuensis*, 217–226.

Keevallik S. 2003b. Possibilities of reconstruction of the wind regime over Tallinn Bay. *Proc. Estonian Acad. Sci. Eng*., 9 (3), 209–219.

Keevallik S., Soomere T. 2004. Trends in wind speed over the Gulf of Finland 1961–2000. In: Isemer H.-J. (Ed.), *Fourth Study Conference on BALTEX, Scala Cinema, Gudhjem, Bornholm, Denmark, 24–28 May 2004*. Conference Proceedings, International BALTEX Secretariat, 29, 129–130.

Keevallik S., Soomere T. 2009. Seasonal and diurnal variations of wind parameters at Pakri. *Estonian J. Eng*., 15 (3), 227–239.

Kelpšaite L., Herrmann H., Soomere T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proc. Estonian Acad. Sci.*, 57 (4), 225–231.

Kelpšaite L., Parnell K., Soomere T. 2009. Energy pollution: the relative importance of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea. *J. Coast. Res.*, SI 56, 812–816.

Kelpšaite L., Dailidiene I., Soomere T. 2011. Changes in wave regime at the south-eastern coast of the Baltic Proper 1993–2008. *Boreal Env. Res*., 16 (Suppl. A), 220–232.

Komen G.J., Cavaleri L., Donelan M., Hasselmann K., Hasselmann S., Janssen, P. A. E. M. 1994. *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambridge, 532 pp.

Kriezi E. E., Broman B. 2008. Past and future wave climate in the Baltic Sea produced by the SWAN model with forcing from the regional climate model RCA of the Rossby Centre. In: *IEEE/OES US/EU-Baltic International Symposium*, May 27–29, Tallinn, Estonia, IEEE, 360–366.

Kull A. 2005. Relationship between interannual variation of wind direction and wind speed. *Publ. Inst. Geogr. Univ. Tartuensis*, 97, 62–73.

Kushnir Y., Cardone V. J., Greenwood J. G., Cane M. A. 1997. The recent increase in North Atlantic wave heights. *J. Climate*, 10, 2107–2113.

Laanearu J., Koppel T., Soomere T., Davies P. A. 2007. Joint influence of river stream, water level and wind waves on the height of sand bar in a river mouth. *Nordic Hydrol*., 38 (3), 287–302.

Lehmann A., Myrberg K. 2008. Upwelling in the Baltic Sea – A review. *J. Marine Syst*., 74, Suppl. S, S3–S12.

Lehmann A., Getzlaff K., Harlaß J. 2011. Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. *Clim. Res.*, 46, 185–196.

Lehmann A., Hinrichsen H.-H, Getzlaff K. 2013. Identifying potentially high risk areas for environmental pollution in the Baltic Sea. *Boreal Environ. Res*., in press http://www.borenv.net/BER/pdfs/preprints/Lehmann.pdf

Leppäranta M. 2012. Ice season in the Baltic Sea and its climatic variability. In *From the Earth's core to outer space.* Haapala I. (ed.), Springer-Verlag, 137, 139–149

Leppäranta M. 2013. Land-ice interaction in the Baltic Sea. *Estonian J. Earth Sci*., 62 (1), 2–14.

Leppäranta M., Myrberg K. 2009. *Physical oceanography of the Baltic Sea*. Springer Praxis, 378 pp.

Liu P. C., Chen H. S., Doong D.-J., Kao C. C., Hsu Y.-J. G. 2008. Monstrous ocean waves during typhoon Krosa. *Ann. Geophys.*, 26, 1327–1329.

Lopatukhin L. I., Bukhanovsky A. V., Ivanov S. V., Tshernyshova E. S. (Eds.). 2006a. *Handbook of wind and wave regimes in the Baltic Sea, North Sea, Black Sea, Azov Sea and the Mediterranean*. Russian Shipping Registry, Saint Petersburg, 450 pp. (in Russian).

Lopatukhin L. I., Mironov M. E., Pomeranets K. S., Trapeznikov Yu. A., Tshernyshova E. S. (Лопатухин Л. И., Миронов М. Е., Померанец К. С., Трапезников Ю. А., Чернышева Е. С.) 2006b. Estimates of extreme wind and waves in the eastern Gulf of Finland (Оценки экстремального ветра и волнения в восточной части Финского залива). *Изв. ВНИИГ*, 245, 145–155 (in Russian).

Mårtensson N., Bergdahl L. 1987. *On the wave climate of the Southern Baltic*. Report Series A:15, Department of Hydraulics, Chalmers University of Technology, Göteborg.

Mietus M. (co-ordinator). 1998. *The climate of the Baltic Sea Basin.* Marine meteorology and related oceanographic activities 41, World Meteorological Organisation, Geneva, 64 pp.

Mietus M., von Storch H. 1997. *Reconstruction of the wave climate in the Proper Baltic Basin, April 1947–March 1988*. GKSS Report 97/E/28, Geesthacht, 30 pp.

Myrberg K., Ryabchenko V., Isaev A., Vankevich R., Andrejev O., Bendtsen J., Erichsen A., Funkquist L., Inkala A., Neelov I., Rasmus K., Rodriguez Medina M., Raudsepp U., Passenko J., Söderkvist J., Sokolov A., Kuosa H., Anderson T. R., Lehmann A., Skogen M. D. 2010. Validation of three-dimensional hydrodynamic models in the Gulf of Finland based on a statistical analysis of a six-model ensemble. *Boreal Env. Res*., 15, 453–479.

Orlenko L. R., Lopatukhin L. I., Portnova G. L. (Eds.). 1984. *Studies of the hydrometeorological regime of Tallinn Bay*. Gidrometeoizdat, Leningrad, 152 pp. (in Russian).

Orviku K., Jaagus J., Kont A., Ratas U., Rivis R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. *J. Coast. Res.*, 19 (2), 364–375.

Overeem I., Anderson R. S., Wobus C. W., Clow G. D., Urban F. E., Mattel N. 2011. Sea ice loss enhances wave action at the Arctic coast. *Geophys. Res. Lett.*, 38, L17503.

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

Paplińska B. 2001. Specific features of sea waves in the Pomeranian Bay, *Arch. Hydro-Eng. Environ. Mech*., 48 (2), 55–72.

Pettersson H. 1994. *Directional wave statistics from the southern Bothnian Sea 1992*. Int. Rep., 1994 (5), Finn. Inst. Mar. Res., 23 pp.

Pettersson H. 2001. Directional wave statistics from the Gulf of Finland 1990–1994. MERI – *Report Series of the Finn. Inst. Mar. Res*, 44, 1–37 (in Finnish).

Pettersson H. 2004. *Wave growth in a narrow bay*. PhD Thesis, Finninsh Institute of Marine Research, Contributions no. 9.

Pettersson H., Boman H. 2002. High waves and sea level during the November storm. In: Annual report 2001. Finninsh Institute of Marine Research, Helsinki, 7.

Pettersson H, Kahma K., Tuomi L. 2010. Predicting wave directions in a narrow bay. *J. Phys. Oceanogr*., 40 (1), 155–169.

Pindsoo K., Soomere T., Zujev M. 2012. Decadal and long-term variations in the wave climate at the Latvian coast of the Baltic Proper. *Proceedings of the IEEE/OES Baltic 2012 International Symposium "Ocean: Past, Present and Future. Climate Change Research, Ocean Observation & Advanced Technologies for Regional Sustainability,* Lithuania, IEEE, 8 pp.

Pryor S. C., Barthelmie R. J. 2003. Long-term trends in near-surface flow over the Baltic. *Int. J. Climatol.*, 23, 271–289.

Pryor S. C., Barthelmie R. J. 2010. Climate change impacts on wind energy: a review. *Renew. Sust. Energy Rev.*, 14, 430–437.

Resio D. T. 1993. *Program WAVAD: Global/regional wave model for wave prediction in deep and/or shallow water*. Offshore & Coastal Technologies Inc. (OCTI), Vicksburg, MS, 26 pp.

Rosenhagen G., Tinz B. 2013. New historical data of the southern Baltic Sea coasts. In: Reckermann M., Köppen S. (Eds.), *7th Study Conference on BALTEX, 10–14 June 2013, Borgholm, Island of Öland, Sweden*, Conference Proceedings, International BALTEX Secretariat, Publication No. 53, 84.

Russian Shipping Registry 1974. *Wind and waves in oceans and seas*. Part II. Data about wind and wave regime in semi-enclosed seas. Vol.1 – The Baltic Sea.

Ryabchuk D., Sukhacheva L., Spiridonov M., Zhamoida V., Kurennoy D. 2009. Coastal processes in the Eastern Gulf of Finland – possible driving forces and connection with the near-shore zone development. *Estonian J. Eng.*, 15, 151–167.

Ryabchuk D., Kolesov A., Chubarenko B., Spiridonov M., Kurennoy D., Soomere T. 2011. Coastal erosion processes in the eastern Gulf of Finland and their links with long-term geological and hydrometeorological factors. *Boreal Env. Res.*, 16 (Suppl. A), 117–137.

Rzheplinsky G. V. (Ed.) 1965. *Wave and wind atlas for the Baltic Sea*. Gidrometeoizdat, Leningrad (in Russian).

Rzheplinsky G. V., Brekhovskikh Yu. P. (Eds.) 1967. *Wave atlas for the Gulf of Finland*. Gidrometeoizdat, Leningrad (in Russian).

Räämet A. 2010. *Spatio-temporal variability of the Baltic Sea wave fields*. PhD thesis. TUT Press, Tallinn, 169 pp.

Räämet A., Suursaar Ü., Kullas T., Soomere T. 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *J. Coast. Res.*, SI 56, vol. I, 257–261.

Räämet A., Soomere T. 2010. Stormy and calm wave seasons in the coastal waters of Estonia. *Estonian J. Earth Sci.*, 59, 100–113.

Schmager W. G. 1979. *Atlas zur Ermittlung der Wellenhöhe in der südlichen Ostsee.* Seehydrographischer Dienst der DDR. XIV, Rostock, 115 pp. (in German).

Schmager G., Fröhle P., Schrader D., Weisse R., Müller-Navarra S. 2008. Sea state, tides. In: Feistel R., Nausch G., Wasmund N. (Eds.), *State and evolution of the Baltic Sea 1952–2005*. Wiley, 143–198.

Seifert T., Tauber F., Kayser B. 2001. A high resolution spherical grid topography of the Baltic Sea, 2nd edition. *Baltic Sea Science Congress*, Stockholm, 25–29 November 2001, Poster #147.

Seymour R. J. 1977. Estimating wave generation on restricted fetches. *J. Waterw. Port Coast. Ocean Div.*, 103, 251–264.

Siegismund F., Schrum C. 2001. Decadal changes in the wind forcing over the North Sea. *Clim. Res.*, 18, 39–45.

Smith S.R., Legler D.M., Verzone K.V. 2001. Quantifying uncertainties in NCEP reanalyses using high-quality research vessel observations. *J. Clim.*, 14, 4062–4072.

Sooäär J., Jaagus J. 2007. Long-term changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proc. Estonian Acad. Sci. Eng.*, 13 (3), 189–200.

Soomere T. 2001. Wave regimes and anomalies off north-western Saaremaa Island. *Proc. Estonian Acad. Sci. Eng.*, 7, 157–173.

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

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

Soomere T. 2008. Extremes and decadal variations of the northern Baltic Sea wave conditions. In: Pelinovsky E., Kharif Ch. (Eds.), *Extreme ocean waves*. Springer, 139–157.

Soomere T. 2013. Extending the observed Baltic Sea wave climate back to the 1940s. *J. Coast. Res.*, Special Issue No. 65, 1969–1974

Soomere T., Healy T. 2008. Escalating extremes over descending trends of the northern Baltic Sea wave fields. In Wallendorf L., Ewing L., Jones C., Jaffe B. (Eds), *Solutions to coastal disasters. 2008*. American Society of Civil Engineers, 129–138.

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

Soomere T., Keevallik S. 2003. Directional and extreme wind properties in the Gulf of Finland. *Proc. Estonian Acad. Sci. Eng.*, 9, 73–90.

Soomere T., Kurkina, O. (Соомере Т., Куркина О.) 2011. Статистика экстремального волнения в юго-западной части Балтийского моря (Statistics of extreme wave conditions in the south-western Baltic Sea), *Фундаментальная и прикладная гидрофизика* (*Fundamental and Applied Hydrophysics*), 4 (4), 43–57 (in Russian).

Soomere T., Räämet A. 2011a. Long-term spatial variations in the Baltic Sea wave fields. *Ocean Science*, 7 (1), 141–150.

Soomere T., Räämet A. 2011b. Spatial patterns of the wave climate in the Baltic Proper and the Gulf of Finland. *Oceanologia*, 53 (1-TI), 335–371.

Soomere T., Räämet A. 2013. Decadal changes in the Baltic Sea wave heights. *J. Marine Syst.*, doi: 10.1016/j.jmarsys.2013.03.009

Soomere T., Behrens A., Tuomi L., Nielsen J.W. 2008a. Wave conditions in the Baltic Proper and in the Gulf of Finland during windstorm Gudrun. *Nat. Hazards Earth Syst. Sci.*, 8, 37–46.

Soomere T., Myrberg K., Leppäranta M., Nekrasov A. 2008b. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia*, 50, 287–362.

Soomere T., Zaitseva-Pärnaste I., Räämet A., Kurennoy T. (Соомере Т., Зайцева-Пярнасте И., Ряямет А., Куренной Д.), 2010. О пространственно-временной изменчивости полей волнения Финского залива (Spatio-temporal variations of wave fields in the Gulf of Finland). *Фундаментальная и прикладная гидрофизика* (*Fundamental and applied hydrophysics*), 4(10), 90–101. Санкт-Петербург: Nauka (in Russian).

Soomere T., Weisse R., Behrens A. 2012. Wave climate in the Arkona Basin, the Baltic Sea, *Ocean Science*, 8(2), 287–300.

Soomere T., Pindsoo K., Bishop S. R., Käärd A., Valdmann A. 2013. Mapping wave set-up near a complex geometric urban coastline. *Nat. Hazards Earth Syst. Sci. Discuss.*, 1, 1651–1688.

Sooäär J., Jaagus J. 2007. Long-term changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proc. Estonian Acad. Sci. Eng*., 13 (3), 189–200.

Sparre A. 1982. *The climate of Denmark; Summaries of observations from light vessels II: Waves and currents at the surface*. Danish Meteorological Institute Climatological Papers, 9.

Sterl A., Komen G. J., Cotton P. D. 1998. Fifteen years of global wave hindcasts using winds from the European Centre for Medium-Range Weather Forecasts reanalysis: validating the reanalyzed winds and assessing the wave climate. *J. Geophys. Res.*, 103 (C3), 5477–5492.

Sterl A., Caires S. 2005. Climatology, variability and extrema of ocean waves – the web-based KNMI/ERA-40 wave atlas. *Int. J. Climatol.*, 25, 963–977.

St-Hilaire-Gravel D., Forbes D. L., Bell T. 2012. Multitemporal analysis of a gravel-dominated coastline in the Central Canadian Arctic Archipelago. *J. Coast. Res.*, 28 (2), 421–441.

Suursaar Ü. 2010. Waves, currents and sea level variations along the Letipea – Sillamäe coastal section of the southern Gulf of Finland. *Oceanologia*, 52 (3), 391–416.

Suursaar Ü. 2013. Locally calibrated wave hindcasts in the Estonian coastal sea in 1966–2011. *Estonian J. Earth Sci*., 62 (1), 42–56.

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

Suursaar Ü., Jaagus J., Kont A., Rivis R., Tõnisson H. 2008. Field observations on hydrodynamic and coastal geomorphic processes off Harilaid Peninsula (Baltic Sea) in winter and spring 2006–2007. *Estuar. Coast. Shelf Sci*., 80 (1), 31–41.

Suursaar Ü., Kullas T. 2009a. Decadal variations in wave heights off Cape Kelba, Saaremaa Island, and their relationships with changes in wind climate. *Oceanologia*, 51 (1), 39–61.

Suursaar Ü., Kullas T. 2009b. Decadal changes in wave climate and sea level regime: the main causes of the recent intensification of coastal geomorphic processes along the coasts of Western Estonia? In: *Coastal Processes.* WIT Transactions on Ecology and Environment, 126, 105–116.

Swail V. R., Cardone V. J., Cox A. T. 1998. A long term North Atlantic wave hindcast. In: *Proc. 5th International Workshop on Wave Hindcasting and Forecasting,* January 26-30, 1998, Melbourne, Florida, USA.

Swail V. R., Ceccacci E. A., Cox A. T. 2000. The AES40 North Atlantic wave reanalysis: validation and climate assessment. In: *6th International Workshop on Wave Hindcasting and Forecasting,* November 6–10, 2000, Monterey, California, USA.

Toffoli A., Lefevre J. M., Bitner-Gregersen E., Monbaliu J. 2005. Towards the identification of warning criteria: analysis of a ship accident database. *Appl. Ocean Res*., 27 (6), 281–291.

Tuomi L., Pettersson H., Kahma K. 1999. Preliminary results from the WAM wave model forced by the mesoscale EUR-HIRLAM atmospheric model. *MERI – Report series of the Finnish Institute of Marine Research*, 40, 19–23.

Tuomi L., Kahma K. K., Pettersson H. 2011. Wave hindcast statistics in the seasonally ice-covered Baltic Sea, *Boreal Environ. Res*., 16, 451–472.

Tuomi, L., Kahma, K. K., Fortelius C. 2012. Modelling fetch-limited wave growth from an irregular shoreline. *J. Marine Syst*., 105, 96–105.

Tõnisson H., Orviku K., Jaagus J., Suursaar Ü., Kont A., Rivis R. 2008. Coastal damages on Saaremaa Island, Estonia, caused by the extreme storm and flooding on January 9, 2005. *J. Coast. Res.*, 24 (3), 602–614.

[USACE] U.S. Army Corps of Engineers 2002. *Coastal Engineering Manual*, No. 1110-2-1100. Washington D.C.

Uppala S. M., Kållberg P. W., Simmons A. J., Andrae U., da Costa Bechtold V., Fiorino M., Gibson J. K., Haseler J., Hernandez A., Kelly G. A., Li X., Onogi K., Saarinen S., Sokka N., Allan R. P., Andersson E., Arpe K., Balmaseda M. A., Beljaars A. C. M., van de Berg L., Bidlot J., Bormann N., Caires S., Chevallier F., Dethof A., Dragosavac M., Fisher M., Fuentes M., Hagemann S., Holm E., Hoskins B. J., Isaksen L., Janssen P. A. E. M., Jenne R., McNally A. P., Mahfouf J. F., Morcrette J.-J., Rayner N. A., Saunders R. W., Simon P., Sterl A., Trenberth K. E., Untch A., Vasiljevic D., Viterbo P., Woollen J. 2005. The ERA-40 re-analysis. *Q. J. Meteorol. Soc*., 131, 2961–3012.

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

Viška M., Soomere T. 2012. Hindcast of sediment flow along the Curonian Spit under different wave climates. In: *Proceedings of the IEEE/OES Baltic 2012 International Symposium "Ocean: Past, Present and Future. Climate Change Research, Ocean Observation & Advanced Technologies for Regional Sustainability,"* May 8–11, Klaipėda, Lithuania. IEEE Conference Publications, 7 pp. doi 10.1109/BALTIC.2012.6249195

Wang D. W., Mitchell D. A, Teague W. J., Jarosz E., Hulbert M. S. 2005. Extreme waves under Hurricane Ivan. *Science*, 309, 896.

Wang X. L., Swail V. R. 2002. Trends of Atlantic wave extremes as simulated in a 40-yr wave hindcast using kinematically reanalyzed wind fields. *J. Clim.*, 15, 1020–1035.

WASA Group 1995. Changing storm and wave climate in the northeast Atlantic and adjacent seas? In: *Proc. 4th International Workshop on Wave Hindcasting and Forecasting, Banff, Canada*, GKSS Report 96/E/61, 31–44.

WASA Group 1998. Changing waves and storms in the Northeast Atlantic? *Bull. Amer. Meteor. Soc.*, 79 (5), 741–760.

Weisse R., Günther H., Feser F. 2002. A 40-year high-resolution wind and wave hindcast for the southern North Sea. In: *Proc. 7th International Workshop on Wave Hindcasting and Forecasting*, October 21–25, 2002, Banff, Alberta, Canada.

Weisse R., von Storch H., Feser F. 2005. Northeast Atlantic and North Sea storminess as simulated by a Regional Climate Model during 1958–2001 and comparison with observations. *J. Clim.*, 18, 465–479.

Weisse R., Plüß A. 2006. Storm-related sea level variations along the North Sea coast as simulated by a high-resolution model 1958–2002. *Ocean Dynamics*, 56, 16–25.

Weisse R., Günther H. 2007. Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958–2002. *Ocean Dynamics*, 57 (3), 161–172.

Weisse R., von Storch H. 2010. *Marine climate and climate change. Storms, wind waves and storm surges*. Springer-Verlag, Berlin, Heidelberg, New York, 220 pp.

WMO 2001. *WMO Guide to the applications to marine climatology*. WMO Publication No. 781, Geneva, 157 pp.

Wulff F., Rahm L., Larsson P. (Eds.) 2001. *A systems analysis of the Baltic Sea*. Springer-Verlag, Berlin, 455 pp.

Zujev M. 2013. *Wave climate at the eastern Baltic Sea coast*. MSc Thesis, Tallinn University of Technology, 74 pp.

Özger M., Sen Z. 2007. Prediction of wave parameters by using fuzzy logic approach. *J. Ocean Eng*., 34 (3–4), 460–469.

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Finally, my sincerest thanks go to my family: my parents Larissa Zaytseva and Oleg Zaytsev, my husband Einar Pärnaste and my son Robert, my sister Olga, brother-in law Denis and niece Sonja. Thank you for your love, support and believing in me in spite of everything. I dedicate this thesis to you.

Abstract

This thesis makes an attempt to reconstruct the basic features of the nearshore wave climate of the eastern Baltic Sea and the Gulf of Finland from historical visual observations at eight coastal measurement sites in 1954–2011. The goal was to identify and quantify the core changes and trends in the main properties of waves, to identify spatial variability of the wave climate in this region, especially concerning the wave height, and to establish the magnitude of decadal variability in the wave properties in the eastern Baltic Sea.

While the accuracy of single observations is not particularly high, statistical distributions of various wave properties (wave height, period, approach direction) reasonably match similar distributions obtained using instrumental measurements and numerical simulations. The average properties of the wave fields extracted from visual observations are consistent with the existing knowledge. The typical long-term average significant wave height in the nearshore is 0.7–0.8 m. The wave regime is highly intermittent. The majority of wave periods are in the range of 2–4 s in the nearshore and 3–6 s offshore. The highest waves once in about 50 years may reach 6 m (periods 11–12 s) near Vilsandi, 5 m (periods 9–10 s) near Pakri and 4 m (periods 7–8 s) near Narva-Jõesuu. The distribution of wave approach directions has a two-peak appearance. The seasonal course of the wave heights matches the similar course of wind speed, with May usually the calmest month and November the month with the highest waves.

Interannual variations in the mean wave height were coherent along the entire eastern Baltic Sea coast from the mid-1950s until the end of the 1980s. Later on the years with a relatively large mean height in the Baltic Proper correspond to comparatively low wave intensity in the eastern Gulf of Finland. Visual observations suggest that wave activity decreased in the 1950s and 1960s and was at its lowest at the end of the 1980s. The phase of relatively high wave activity in the northern Baltic Proper in the 1990s was accompanied by very low annual mean wave heights at the south-eastern coast of the Baltic Sea. The described changes were probably caused by changes in the wind direction and possibly by a clustering of low pressure systems in the Sea of Bothnia in the 1990s.

No long-term trend in the annual mean wave height is evident in the eastern Baltic Proper. Wave heights have gradually decreased in the south-eastern Gulf of Finland since the 1960s. A major rotation of the predominant wave approach direction by about 90° since the end of the 1970s has been identified in this region. There is no evident correlation between the commonly used wave characteristics (such as the annual mean wave height or the annual mean energy) and the length of the ice season. A reasonable measure of the impact of ice cover on waves is the annual integral wave energy flux

Resümee

Eesti kui mereriigi privileeg on võimalus kasutada meie rannikuvööndit nii majandustegevuseks (sadamate rajamine, kaubavedu, puhkealad) kui ka unikaalsete looduskoosluste säilitamiseks. Samas on rannikud tormide ja kõrge veeseisuga esineva lainetuse tõttu tugeva loodusliku surve all. Läänemere lainetus on tundlik isegi väikeste väliste tingimuste muutuste suhtes. Erinevalt avaookeanist võib tuule suuna muutumine põhjustada lainekõrguse märgatavat kasvu. Ebatavalisest suunast saabuvad lained võivad kahjustada randu ja insener-tehnilisi rajatisi.

Väitekirjas on rekonstrueeritud rannalähedase lainetuse peamised omadused (teisisõnu, lainekliima peamised parameetrid) ning nende ajalis-ruumilise muutlikkuse põhijooned Läänemere idaosas ja Soome lahes visuaalsete lainevaatluste andmestike alusel. Kasutatakse vaatlusi kaheksast kohast. Detailselt on analüüsitud kolme andmestikku Eestist ja üht Leedust 1954–2009. On näidatud, et lainetuse parameetrid (nt aasta keskmine lainekõrgus) on kõnesoleva mereala üksikutes osades viimastel aastakümnetel drastiliselt muutunud.

On näidatud, et kuigi üksikute lainevaatluste täpsus ja usaldusväärsus on tagasihoidlikud, on lainete peamiste omaduste (keskmine lainekõrgus, tüüpiline periood, levikusuund) rekonstrueeritud keskmised või tüüpilised väärtused ning nende empiirilised jaotused heas kooskõlas nende suuruste modelleeritud ja instrumentaalselt mõõdetud väärtustega. Keskmine lainekõrgus Läänemere idaosa rannalähedases meres on 0,7–0,8 m. Lainete tüüpilised perioodid rannalähedases meres (2–4 s) on lühemad kui avamerel (3–6 s). Lained saabuvad valdavalt kahest kindlast suunast. Lainekõrguse sesoonne käik järgib tuule sesoonset muutumist: mais on lainekõrgus tavaliselt väikseim ja novembris suurim.

Aastane lainekõrgus muutus kõigis Läänemere idaranniku vaatluspunktides samas rütmis alates 1950ndatest kuni 1980ndate lõpuni. Alates 1990ndatest on Narva-Jõesuus keskmine lainekõrgus suurim aastail, mil see on madal Läänemere avaosas ja vastupidi. Lainekõrgus kahanes kogu Läänemere idaosas 1950ndatel ja 1960ndatel ning oli eriti tagasihoidlik 1980ndate lõpul. Aastail, mil Läänemere avaosa põhjapoolses sektoris oli lainekõrgus ebatavaliselt suur (1990ndatel), oli lainekõrgus mere kaguosas tavapärasest märksa madalam. Selle nähtuse tõenäoline põhjus on tsüklonite trajektooride koondumine Botnia merele. Lainekõrguste muutustes ei tuvastatud ühtegi statistiliselt usaldusväärset pikaajalist (üle 30 a) trendi. Vaid Soome lahe edelaosas, Narva-Jõesuus, ilmnes tuntav lainekõrguse kahanemine. Selles piirkonnas identifitseeriti ka lainete leviku valdava suuna pöördumine ligi 90° võrra. Töös identifitseeritud suhteliselt pikaajalised ja tsüklilised muutused lainekõrguses ja laineleviku suunas võivad olla põhjuseks, miks paljud Eesti rannad on lähiminevikus tugevasti kahjustatud.

Näidati, et korrelatsioon jääperioodi pikkuse ja lainetuse mitmesuguste parameetrite vahel avaldub erinevates vaatluskohtades väga erinevalt. Klassikalistest lainetust iseloomustavatest suurustest on tugevaim korrelatsioon jääperioodi pikkuse ja jäävabal ajal aset leidnud summaarse laineenergia voo vahel.

Appendix A: Curriculum Vitae

1. Personal data

Name	Inga Zaitseva-Pärnaste
Date and place of birth	23.11.1983, Russia
Address	Akadeemia tee 21, 12618 Tallinn
Phone	(+372) 620 4156
e-mail	ingaz@ioc.ee

2. Education

Educational institution	Graduation year	Education (field of study / degree)
Tallinn University of Technology	2009	Earth Sciences / Oceanography MSc
Estonian Maritime Academy	2006	Hydrography / Diploma

3. Language competence/skills

Language	Level
Russian	native language
English	average
Estonian	fluent
Dutch	basic skills

4. Special courses and further training

Period	Educational or other organisation
2009	"TRACMASS – A Lagrangian Trajectory code" course, Tallinn University of Technology, Estonia
Mar. 2009	Intense course for young researchers "Statistical software for climate research", Malta
Aug. 2007–Sept. 2007	International Summer School "Waves and Coastal Processes", Tallinn University of Technology, Estonia
2006	Course "Linux Part 1", Den Haag, the Netherlands

5. Professional employment

Period	Organisation	Position
Jan. 2008–to date	Tallinn University of Technology, Institute of Cybernetics	Engineer
Sept. 2006–Feb. 2008	Boskalis Westminster bv.	Hydrographic surveyor

6. Research activity

7.1. Publications

Articles indexed by the ISI Web of Science (1.1):

Zaitseva-Pärnaste I., Soomere T. 2013. Interannual variations of ice cover and wave energy flux in the northeastern Baltic Sea. *Annals of Glaciology*, 54 (62), 175–182.

Zaitseva-Pärnaste I., Soomere T., Tribštok O. 2011. Spatial variations in the wave climate change in the eastern part of the Baltic Sea. *Journal of Coastal Research*, Special Issue 64, vol. I, 195–199.

Soomere T., Zaitseva-Pärnaste I., Räämet A. 2011. Variations in wave conditions in Estonian coastal waters from 1 weekly to decadal scales. *Boreal Environment Research*, 16 (Suppl. A), 175–190.

Räämet A., Soomere T., Zaitseva-Pärnaste I. 2010. Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. *Proceedings of the Estonian Academy of Sciences*, 59 (2), 182–192.

Zaitseva-Pärnaste I., Suursaar Ü., Kullas T., Lapimaa S., Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. *Journal of Coastal Research*, Special Issue 56, vol. I, 277–281.

Peer-reviewed articles in other international research journals (1.2):

Parnell K., Delpeche N., Didenkulova I., Dolphin T., Erm A., Kask A., Kelpšaite L., Kurennoy D., Quak E., Räämet A., Soomere T., Terentjeva A., Torsvik T., Zaitseva-Pärnaste I. 2008. Far-field vessel wakes in Tallinn Bay. *Estonian Journal of Engineering*, 14 (4), 273–302.

Soomere T., Zaitseva I. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proceedings of the Estonian Academy of Sciences. Engineering*, 13 (1), 48–64.

Chapters in peer-reviewed collections (3.1):

Соомере Т., Зайцева-Пярнасте И., Ряямет А., Куренной Д. 2010. О пространственно-временной изменчивости полей волнения Финского залива.

Фундаментальная и прикладная гидрофизика, Санкт-Петербург, Nauka, 90–101.

Articles published in conference proceedings (3.4):

Зайцева-Пярнасте И., Соомере Т. 2009. Сезонные и долгопериодные изменения характеристик ветровых волн в центральной части Балтийского моря. In: *Литодинамика донной контактной зоны океана: материалы Международной конференции, посвященной 100-летию со дня рождения профессора В.В. Лонгинова, 14–17 сентября 2009, г. Москва*, Акивис Т. М., Пыхов Н. В. (Eds.), ГЕОС, Москва, 25–27.

Conference abstracts (5.2):

Zaitseva-Pärnaste I., Soomere T. 2012. Interannual, decadal and long-term variations in the wave fields. In: *2012 IEEE/OES Baltic International Symposium "Ocean: Past, Present and Future. Climate Change Research, Ocean Observation & Advances Technologies for Regional Sustainability,"* May 8–11, Klaipėda, Lithuania, Presentation Abstracts, Klaipėda, Baltic Valley, 100.

Zaitseva-Pärnaste I., Soomere T. 2010. Wave climate in the Eastern part of the Baltic Sea. In: The *5th International Student Conference on Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region*. October 6–8, Palanga, Lithuania, Conference Proceedings, Klaipėda, Klaipėda University, 113–114.

Zaitseva-Pärnaste I., Soomere T. 2010. Long-term variations of wave heights and its comparison with ice conditions in Estonian coastal waters. In: *The 10th International Marine Geological Conference "The Baltic Sea Geology – 10."* VSEGEI, August 24–28, Saint Petersburg, Russia, Abstracts Volume, Press VSEGEI, 156–157.

Tribštok O., Zaitseva-Pärnaste I., Soomere T. 2010. Changes in wave heights at Estonian and Lithuanian coasts based on historical wave observations. In: *The 10th International Marine Geological Conference "The Baltic Sea Geology – 10."* VSEGEI, August 24–28, Saint Petersburg, Russia, Abstracts Volume, Press VSEGEI, 135–136.

Zaitseva I., Suursaar Ü., Soomere T. 2009. Seasonal and long-term variations of wave conditions in Estonian coastal waters. In: *BSSC 2009 (7th Baltic Sea Science Congress 2009.* August 17–21, Tallinn, Estonia, Abstract Book, Tallinn University of Technology, 148.

Zaitseva-Pärnaste I., Suursaar Ü., Kullas T., Lapimaa S., Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. In: *The 10th International Coastal Symposium.* April 13–18, Lisbon, Portugal, Book of Abstracts of: ICS 2009, Lisbon: e-GEO, Universidade Nova de Lisboa, 63.

Soomere T., Zaitseva I., Kelpšaite L. 2008. Mismatch of trends of average wave activity and extreme wave conditions in the northern Baltic Sea. *Geophysical Research Abstracts*, 10, EGU2008-A-04128, 4 pp.

Zaitseva-Pärnaste I. 2008. Long-term variations of wave conditions in the northern Baltic Sea derived from visual observations from Vilsandi, Pakri and Narva-Jõesuu. In: *The 3rd International Student Conference Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region.* October 9–13, Klaipėda, Lithuania, Book of Abstracts, 44.

Zaitseva I., Soomere T. 2008. On long-term variations of wave conditions in the northern Baltic Sea. In: *US/Eu-Baltic 2008 International Symposium "Ocean Observations, Ecosystem-based management & forecasting".* May 27–29, Tallinn, Estonia, Book of Abstracts, 169–170.

Soomere T., Zaitseva I. 2007. Long-term variations of wave properties in the northern Baltic Proper. In: *Baltic Sea Science Congress.* March 19–22, Rostock, Germany, Abstract volume, Part 1, Rostock University, 93.

7.2. Conference presentations

Zaitseva-Pärnaste I., Soomere T. 2012. Interannual variations of ice cover and wave energy flux in the north-eastern Baltic Sea. Poster presentation at the *International Symposium on "Seasonal Snow and Ice".* May 28–June 1, Lahti, Finland.

Zaitseva-Pärnaste I., Soomere T. 2010. Wave climate in the eastern part of the Baltic Sea. Poster presentation at the *5th International Student Conference on Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region.* October 6–8, Palanga, Lithuania.

Zaitseva-Pärnaste I., Soomere T. 2010. Long-term variations of wave heights and its comparison with ice conditions in Estonian coastal waters. Oral presentation at the *10th International Marine Geological Conference "The Baltic Sea Geology – 10".* August 24–28, Saint Petersburg, Russia.

Zaitseva-Pärnaste I., Räämet A., Soomere T. 2010. Comparison between modelled and measured wind wave parameters in Estonian coastal waters. Poster presentation at the *2nd International Conference on the Dynamics of Coastal Zone of Non-Tidal Seas.* June 27–30, Baltiysk, Kaliningrad Oblast, Russia.

Zaitseva-Pärnaste I., Soomere T. 2009. Seasonal and long-term variations of wave conditions in Estonian coastal waters. Oral presentation at the *International Conference on Complexity of Nonlinear Waves.* October 5–7, Tallinn, Estonia.

Zaitseva-Pärnaste I., Soomere T. 2009. Long term variation in wave fields in the Baltic Proper. Poster presentation at the *International Conference on Lithodynamics of bottom contact zone of the ocean*. September 14–17, Moscow, Russia.

Zaitseva I., Soomere T. 2009. Long term variation in wave fields in the Baltic Proper. Oral presentation at the *SEAMOCS Closure Meeting.* September 8–10, Toulouse, France.

Zaitseva I., Suursaar Ü., Soomere T. 2009. Seasonal and long-term variations of wave conditions in Estonian coastal waters. Oral presentation at the *7th Baltic Sea Science Congress.* August 17–21, Tallinn, Estonia.

Zaitseva-Pärnaste I., Suursaar Ü., Kullas T., Lapimaa S., Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. Oral presentation at the *10th International Coastal Symposium*. April 13–18, Lisbon, Portugal.

Zaitseva I., Kelpšaite L. 2008. Wave regime changes at the Baltic Sea Eastern coast. Oral presentation at the *SEAMOCS Network Meeting and Conference*. October 22–25, Oslo, Norway.

Zaitseva-Pärnaste I., 2008. Long-term variations of wave conditions in the northern Baltic Sea derived from visual observations from Vilsandi, Pakri and Narva-Jõesuu. Poster presentation at the *3rd International Student Conference "Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region"*. October 9–12, Klaipėda, Lithuania.

Zaitseva I., Soomere T. 2008. On long-term variations of the wave conditions in the northern Baltic Sea. Oral presentation at the *US-EU-Baltic 2008 International Symposium.* May 27–29, Tallinn, Estonia.

Appendix B: Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Inga Zaitseva-Pärnaste
Sünniaeg ja -koht	23.11.1983, Venemaa
Aadress	Akadeemia tee 21, 12618 Tallinn
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e-mail	ingaz@ioc.ee

2. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala / kraad)
Tallinna Tehnikaülikool	2009	Maateadused / Okeanograafia MSc
Eesti Mereakadeemia	2006	Hüdrograafia / Diplom

3. Keelteoskus

Keel	Tase
Vene	emakeel
Inglise	kesktase
Eesti	kõrgtase
Hollandi	algtase

4. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2009	"TRACMASS – A Lagrangian Trajectory code" kursus, Tallinna Tehnikaülikool, Eesti
Mar. 2009	Noorteadlaste intensiivkursus „ Kliimauuringute statistiline tarkvara", Malta
August 2007– September 2007	Rahvusvaheline suvekool "Lained ja rannikuprotsessid", Tallinna Tehnikaülikool
2006	Kursus "Linux Part 1", Haag, Holland

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
Jaanuar 2008–tänaseni	Tallinna Tehnikaülikool, Küberneetika Instituut	Insener
September 2006– Veebruar 2008	Boskalis Westminster bv.	Hüdrograaf

7. Teadustegevus

Teadusartiklite, konverentsiteeside ja konverentsiettekannete loetelu on toodud ingliskeelse CV juures.

Paper I

Soomere T., **Zaitseva I**. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proceedings of the Estonian Academy of Sciences, Engineering*, 13 (1), 48–64.

Proc. Estonian Acad. Sci. Eng., 2007, **13**, 1, 48–64

Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi

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Abstract. Wave conditions, their seasonal cycle and long-term variations in the northern part of the Baltic Sea Proper are studied, based on visual wave observations at the Vilsandi Island near the coast of Saaremaa in 1954–2005. Typical wave periods are from 2 to 4 s. The monthly mean wave height follows the seasonal variation in wind speed and varies from about 0.4 m in April–July to almost 0.8 m in January. The annual mean wave height shows a quasiperiodic behaviour. The wave activity varied insignificantly in the 1960s and 1970s, considerably increased in the 1980s, was the highest just before the turn of the century and is decreasing starting from about 1998.

Key words: wind waves, Baltic Sea, wave climate, visual wave data.

1. INTRODUCTION

Several cases of extremely rough wave conditions at the turn of the millennium [1] and two ferocious winter storms in 2004/2005 [2,3] have reinforced the discussion about whether the wave conditions in the Baltic Sea have become more rough compared to the situation a few decades ago. On the one hand, it is argued in [4] that the apparently increasing storminess in the Baltic Sea has already caused extensive erosion of depositional coasts. On the other hand, possible changes in the wave climate [5,6] have been found marginal, at least until the mid-1990s.

These discussions presume a thorough knowledge of the typical wave conditions. The information about the wave climate of the Baltic Sea, however, is relatively fragmentary. This feature can be partially explained by the fact that both numerical and experimental studies of wave conditions in the Baltic Sea area are very complex tasks. This water body is characterized by a relatively small size, extremely complex geometry, highly varying wind field, extremely rough wave conditions at times, extensive archipelago areas with specific wave propagation properties, and the ice cover during a large part of the year. The global wave data set KNMI/ERA-40 Wave Atlas [7] (based on an atmospheric reanalysis data set covering the period from September 1957 to August 2002 by the European Centre for Medium Range Weather Forecasts) reveals a reliable wave climatology for open ocean conditions. However, the basic wave parameters (such as the 6-hourly significant wave height, the mean zero-upcrossing wave period and the mean wave direction) are presented as an average of a $1.5 \times 1.5°$ area. This resolution is too sparse for the Baltic Sea conditions.

Contemporary wave recorders have been used in the northern Baltic Sea during a few decades [1,8]. High-quality wave data sets exist for the sea areas around Finland since the 1970s [1,8–13]. The wave climate of these areas is fairly well investigated. Regular wave measurements in the central area of the northern Baltic Proper (Fig. 1) were launched in September 1996 [1]. These data are particularly important for understanding the Baltic Sea wave climate; however, this time series is much shorter than 30 years, the interval recommended by the World Meteorological Organization for determining the climatological values of the environmental data [14].

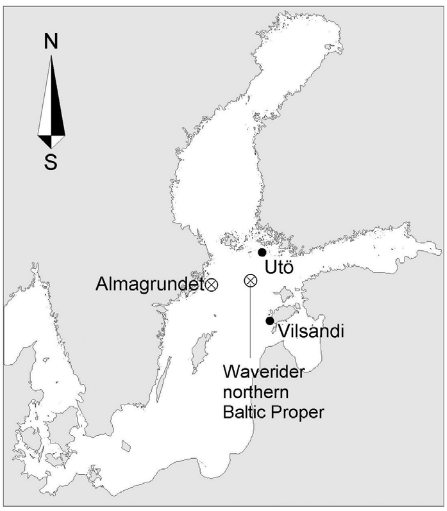

Fig. 1. Location of the observation site at Vilsandi and the wave measurement sites (marked by ⊗), data from which is analysed in [1,16].

Several semi-autonomous wave measurement devices were deployed in the shallow areas of the northern Baltic Sea about three decades ago [15]. A data set, recorded in 1978–2003 near the lighthouse of Almagrundet (the western sector of the northern Baltic Proper, 59°09′ N, 19°08′ E, Fig. 1) has been recently analysed in [16]. The data from the years 1978–1993 were found most reliable. Later recordings at the turn of the century showed quite an irregular behaviour of wave properties and were only partially analysed. This time period is also too short for the reliable description of the local wave climate. Also, the observation site is sheltered from a part of dominating winds. Hardly any instrumentally measured wave data is available from the coastal areas of Estonia, Latvia and Lithuania, except for sporadic measurements made with pressure-based sensors [17,18]. As a result, older sources such as [19,20] are at times still in use in estimates of wave conditions in the eastern part of the Baltic Sea.

Since the waves from the rest of the World Ocean practically do not affect the Baltic Sea waves, the wave properties here can be described with the use of local models. The existing numerical wave studies in the Baltic Sea basin have been recently discussed in [16,17]. The central conclusion is that the spatial distribution of the wave activity reflects the anisotropy of the wind regime in the Baltic Proper [21,22]. Statistically, the regions of the largest wave activity are found along the eastern coasts of the Baltic Proper [23,24]. A number of studies has been performed for limited areas of the Baltic Sea [25–27]. Yet an adequate long-term simulation of the Baltic Sea wave fields is still missing. For that reason, historical sources of wave information are highly valuable for this area.

A reasonable source of the open sea wave information form visual observations from the ships [28]. Such data have been used for description of wave fields also in the Baltic Sea [20]. Even the wave climate changes, estimated from the data observed from merchant ships, are consistent with those obtained from the instrumental records [29,30]. Only wave periods were somewhat underestimated by the observers.

Visual observations from the coast have been frequently interpreted as representing only wave properties in the immediate vicinity of the observation point. For example, visual data from Tallinn Harbour were found to represent wave properties only in the near-coastal regions and inadequate for describing open-sea wave fields [31]. Such data always contain an element of subjectivity, are not necessarily homogeneous in time, usually have a poor spatial and temporal resolution, inadequately reflect waves for several wind directions, reflect waves only during a short observation interval a few times a day, may give a distorted impression of extreme wave conditions because of wave breaking and reflection in shallow water, have many gaps caused either by inappropriate weather conditions or by the presence of ice, etc.

Yet the visual wave data are one of the few sources for detecting the wave climate and its long-term changes. Their basic advantage is the large temporal coverage. For example, records of hydrometeorological parameters at Tallinn Harbour started in 1805 and optionally contained visually estimated wave parameters (R. Vahter, personal communication 2003). In the second half of the 20th century, visual wave observations with the use of a unified procedure (partially with the help of some technical means) were performed in many locations of the eastern coast of the Baltic Sea.

In this paper, an attempt is made to estimate certain basic features of the wave climate and their long-term changes in the eastern sector of the northern Baltic Proper, based on visual wave observations from the coast. The data from the Vilsandi Island, located at the western periphery of the West-Estonian Archipelago are used in the analysis. The data are interpreted as regular samples of wave conditions that apparently reflect the basic properties of the wave climate. We start from the description of the measurement site and the procedure of quantifying the sea state. The quality of the data, the average wave properties at the site, the appearance of the distribution of wave heights and the joint distribution of wave heights and periods are discussed next. Finally we analyse the seasonal and long-term variation of wave heights, based on daily mean wave conditions. The results largely represent type A statistics in terms of the classification of [1]. Except for using all available observations at each day for the estimate of the daily mean wave height, no corrections have been made to compensate for missing values, for the uneven distribution of data, or for ice cover.

2. OBSERVATION SITE, PROCEDURE AND DATA

Regular visual wave observations have been performed at several coastal sites of Estonia during the second half of the 20th century (see www.emhi.ee). The majority of the sites are located either at the coasts of semi-enclosed basins of the Baltic Sea or are open to a few directions. An observation site, apparently well reflecting the open sea wave conditions, is located westwards from Saaremaa at the western coast of the Vilsandi Island (58°22′59″ N, 21°48′55″ E, Fig. 1). This island is also named Felsland on older maps after a limestone cliff along its western coast. Meteorological observations have a long tradition on this island. The first data exist from September 1865 but apparently observations have been performed also earlier.

The meteorological data from this site well reflect the open-sea wind properties [32]. They are frequently used in simulations of waves, water level, or circulation patterns [3,22]. This feature suggests that the observed wave properties also more or less adequately reflect the offshore sea state for most of the wind directions. The wave conditions at this site do not represent offshore wave fields for easterly winds; however, the frequency and strength of such winds is relatively low in this area [32].

Systematic wave observations at Vilsandi have been performed starting from 1954 [33]. The properties of waves, approaching from the western and partially from the northern directions (SW–NNE), are observed from a coastal site located about 1.5 m above the mean water level. For waves approaching from more southern directions, another observation point, located at a light pier, was used. Although waves, observable from the pier, are more affected by the coastline, small islands and shallow areas nearby, this site is more representative for waves, approaching from south and southeast. The seabed in the vicinity of both sites is gently sloping. The 4 m isobath is located at about 200 m from the coastline [33,34]. Therefore the sea area, in which the waves were observed, apparently had a maximum depth of 3–4 m. Wave observations were only performed in daylight. The initial observation times (7:00, 13:00 and 19:00 Moscow time, or GMT +3 hours [35]) were later shifted to 6:00, 12:00 and 18:00 GMT according to the WMO guidelines [14]. This shift obviously has no large influence on the estimates of the wave climate.

The interval between subsequent observations at Vilsandi is often (in particular, in autumn and winter, when only one observation per day is available) much longer than the typical saturation time of rough seas (about 8 hours [36]) in the northern Baltic Proper. The duration of a wave storm seldom exceeds 10 hours (see also [16]). Therefore even the strongest storms, if they were not long enough, or occurred during a night, or were accompanied by low visibility, are not necessarily represented in the data set. Consequently, the observations cannot be used for a reconstruction of the time series of the sea state. Instead, they are interpreted as a set of regular samples reflecting the sea state. Since the number of observations is quite large, the data apparently reflect the basic features of the wave climate at the site.

The number of observed parameters varied greatly in different years. In the first years of observations 1) the type of the sea state, 2) the general appearance of the wave field, 3) the wave direction, 4) the intensity of waves, 5) the maximum and 6) mean wave height, 7) wave steepness, 8) length and 9) period were recorded [35]. The type of the sea state is reflected in terms of 9 categories whether windseas or swell, or their combination dominates. The general appearance of the wave field was described in a scale of 10 qualitative units ranging from calm seas to extremely rough wave conditions. The wave direction was defined (with a resolution of 45°) as the direction from which the waves approached. For a combination of windseas and swell, or for cross seas, the wave parameters were given for the dominating component. If several wave systems had a comparable intensity, the preference was given to waves, propagation direction of which matched the local wind direction. The intensity of waves was characterized in 9 qualitative units ranging from calm seas to exceptionally rough seas. Not all the parameters are independent, and in the course of time the number of recorded properties was reduced. For example, the wave steepness was only observed during a short time and was occasionally replaced by observations of the appearance of the wave field, and the type of sea state has been recorded until 30 July 1961. The basic measurable parameters such as the wave height, direction, period and length have the largest temporal coverage. Although the qualitative characteristics of the sea state apparently cannot be linked with contemporary wave data, they were at times helpful in estimates of the data consistency.

The analysis below is mostly performed for wave heights and to a certain extent for wave periods. The observational procedure resembles the classical zero-crossing method [37]. The observer noted the five highest waves during a 5-minute time interval with an accuracy of 0.25 m for wave heights less than 1.5 m, 0.5 m for wave heights from 1.5 to 4 m, and 1 m for even higher waves. The highest single wave $H_{\max}$ and the mean height H of these 5 waves were filed.

The most widely used measure of wave heights today, the significant wave height H_s, has been originally defined as the average height $H_{1/3}$ of the 1/3 of the highest waves during a certain time interval. In contemporary wave measurement devices and in numerical wave models it is estimated as $H_s = 4\sqrt{m_0}$, where m_0 is the zero-order moment of the spectrum, or, equivalently, the total variance of the water surface displacement [38]. Typical periods of wind waves in the northern Baltic Proper are from 3 to 4 s [16]. Consequently, the mean wave height observed at Vilsandi is formally equivalent to the average height $H_{2.5\%} - H_{3\%}$ of 2.5–3% of the highest waves during the observation interval. Since the number of observed waves was quite small, the mean height usually insignificantly differed from the maximum wave height. The average ratio of $H/H_{\max}$ at Vilsandi is 0.94, thus the two measures are fairly close to each other. The experience with the visual observations, however, proves that the observer's estimate of the wave height represents rather well the significant wave height [29,30]. For that reason we shall interpret the mean wave height, observed at Vilsandi, as an estimate of the significant wave height.

The wave period (or length) was determined as an arithmetic mean from three consecutive observations of passing time (total length) of 10 waves each time. These waves were not necessarily the highest ones. The result could be formally interpreted as an estimate of the mean wave period. The experience with visual observations, however, suggests that the visually observed wave period is only a few tenths of seconds shorter than the peak period [30]. For that reason, we shall interpret the visually observed wave period as an estimate of the peak period.

The properties of waves in the observation area are affected by a number of shallow-water effects such as shoaling, refraction, the wave energy loss due to bottom friction and partial breaking, and partial reflection of wave energy from the underwater slope, among others. Since the water depth at the location, where the wave properties were determined, was less than 4 m, waves higher than 4 m evidently were in the breaking stage. Since the fraction of 4 m and higher waves is less than 0.4% in this area [16], errors in their observation insignificantly affect the overall wave statistics. Although the joint influence of the listed effects may considerably change the heights of the observed waves, in most cases it does not change the dominating wave period. Also, their joint effect apparently does not substantially affect the magnitude of the relative variations of the seasonal and long-term wave properties.

3. DATA PREPROCESSING

The data was recently digitized from the original observation diaries for the years 1954–2005 [33]. All obviously erroneous, ambiguously written or inconsistent entries (for example, the maximum wave height 5 m and the mean wave height 0.5 m, the sea state nearly calm) were omitted. There are many records of the wave height less than 0.25 m in older diaries. They have been digitized as 0.25 m, because completely calm seas are infrequent in this area [16].

As mentioned above, the number of observed wave parameters decreases in the course of time. Only the wave height has been observed during all the years. Both the maximum and mean wave heights are present in the diaries until 1993. Further on mostly only one measure is present although the two entries appear a few times afterwards until 23 April 1998. The wave period has been recorded until 30 April 1994 and the wave direction until 23 April 1998.

The total number of sensible observations, reflecting at least one parameter of the wave field, is 32 449 (Table 1). The majority of observations has been made at noon. Morning and evening observations are more fragmentary. They are absent during the late autumn and winter eventually because of the darkness. At least one sensible observation exists on 15 038 days, that is, on 79% from the total number (18 993) of days. The data coverage in different years and seasons varies greatly (Fig. 2). The gaps from January to March (Figs. 2, 3) apparently are connected with the presence of sea ice. The largest gaps during other seasons are in July–September 1991 (when the meteorological station was closed), and in August–November 1997 (Fig. 3). There are a few other shorter time intervals, which do not contain wave data. During the first years of measurements the data set contains a few unrealistically high waves. In many cases these entries correspond to very rough seas. The method used for correction of such entries is described below.

Table 1. Parameters of wave observations and properties at Vilsandi

	Total	Days covered	Morning	Noon	Evening
Sensible entries of wave data (maximum or mean) in the diaries in 1954–2005 (18 993 days)	32 449	15 038	10 893	14 484	7 072
Inconsistent data	707		206	351	150
Consistent maximum wave height entries	31 742	14 775	10 687	14 133	6 922
Consistent mean wave height entries	27 203	12 256	9 261	11 856	6 086
Sensible wave period entries in 1954–1994 (14 975 days)	28 016	12 553	9 495	12 266	6 255
Zero wave period	13 550		4 812	5 495	3 243
Records represented in Fig. 4	14 466	7 719	4 683	6 771	3 012
Corrected observations of $H_{max} > 4.5$ m	51		12	31	8
Corrected observations of $H > 4$ m	34		11	18	5
Average maximum wave height, m			0.56	0.65	0.48
Average mean wave height, m			0.49	0.57	0.42

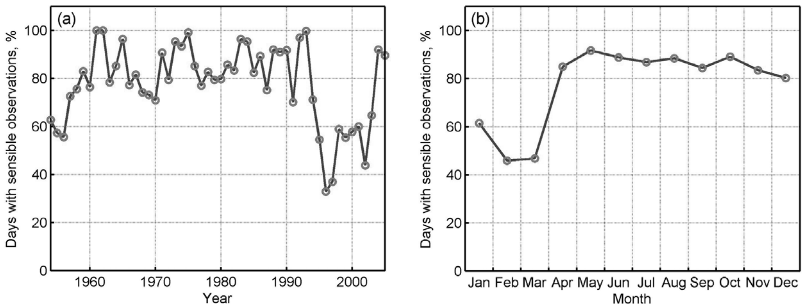

Fig. 2. Percentage of days with at least one sensible wave observation at Vilsandi: (a) in years 1954–2005, (b) in different months.

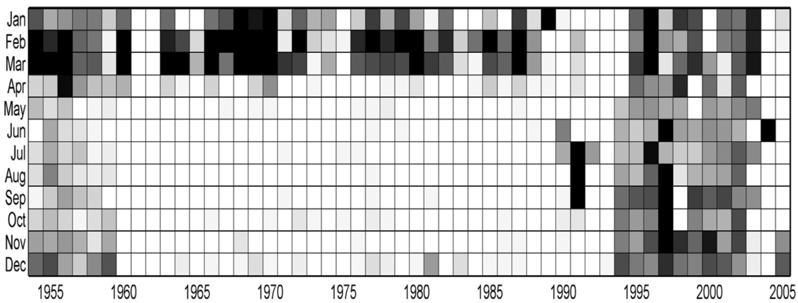

Fig. 3. Temporal distribution of days containing at least one sensible wave observation. The 100% coverage is indicated in white and low coverage corresponds to dark grey.

There are in total 10 838 (10 661) cases (33.4%) when the maximum (mean) wave height is zero. In 9399 cases they both are zero. The majority of such cases apparently correspond to calm seas. However, in some cases the diary reflects a zero wave height but its other entries suggest that the wave height was appreciable. The consistency of such records can be estimated until 30 June 1961 by a comparison with the record of the sea state and later on optionally with the use of another qualitative estimate of wave intensity. The sea state, corresponding to code 0, is perfectly calm and code 1 means very low waves. Code 2 corresponds to the start of breaking of relatively small waves. It is intuitively clear that the wave height under 0.25 m (which could have been filed as $H_{\max} = H = 0$ according to the resolution used) may only correspond to codes 0, 1 or 2. The same is true for the wave intensity that is recorded according to the 9-stage scale (see above). Therefore, in the cases when any qualitative measure of the sea state exceeds 2, the wave height cannot be zero. All such entries

(Table 1) have been omitted from further analysis. The resulting data set consists of 31 742 (27 203) measurements of the maximum (mean) wave height on 14 775 (12 256) days. In nearly all the remaining cases (27 188) the record of the mean wave height was accompanied by the record of the maximum wave height.

For observations where both the mean and maximum wave height were filed, the mean wave height is used below. Since the average ratio of these characteristics is about 0.94, the possible distortion of the wave properties, owing to the potential inhomogeneity of the time series, is fairly minor.

4. OCCURRENCE OF DIFFERENT SEA STATES

The joint distribution of the occurrence of wave heights and mean periods at Vilsandi (Fig. 4) represents all sensible wave observations with non-zero wave

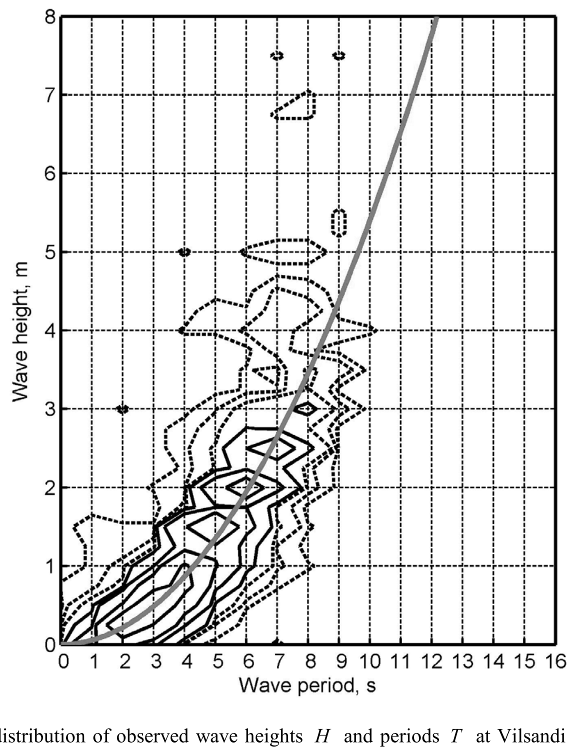

Fig. 4. Joint distribution of observed wave heights H and periods T at Vilsandi in 1954–1994. The wave height step is 0.25 m. The range of periods is shown on the horizontal axis, for example, 1 s means $0.5 \le T < 1.5$ s, 2 s means $1.5 \le T < 2.5$ s etc. Isolines for 1, 3, 10 (dashed lines), 33, 100, 330 and 1000 (solid lines) observed cases are plotted. The bold grey line shows the height of the saturated wave field with the Pierson–Moskowitz spectrum for the given peak period.

period. Since observations of the wave period were made in 1954–1994, the distribution does not reflect the wave properties during the last decade. The total number of records containing sensible wave period is 28 016 on 12 553 days from the total of 14 975 days in 1954–1994. The wave period was zero in 13 550 records. Figure 4 thus represents 14 466 observations on 7719 days. Since there are usually more observations on a day during the relatively calm spring and summer seasons than during the relatively windy autumn season (see below), this distribution may have a certain bias towards overestimation of the frequency of mild wave conditions. This bias, however, is very small in Fig. 4 that uses the logarithmically increasing values of the isolines.

This distribution has the shape, typical for the Baltic Sea wave fields [1,16]. The most frequent wave periods are 2–4 s (20–27% of the observations, Fig. 5a), with the largest number of waves with a period of 3 s. The periods from 2 to 3 s usually correspond to wave heights well below 1 m whereas waves with periods of 4 s have a typical height of about 1 m. Wave periods about 5 and 6 s also occur with an appreciable frequency (14 and 8%, respectively) and usually correspond to wave heights of about 1.5–2 m. Wave fields with periods about 7 s occur with a frequency of about 3%. The corresponding wave heights usually are close to 2.5 m. Wave periods over 8 s are seldom and occur with a probability of about 1%.

Wave data, recorded in the northern Baltic Proper [1], at Almagrundet [16] and in the Gulf of Finland [12], contain a certain amount of swell-dominated wave fields with (peak or mean) periods over 10 s. A wave period close to 10 s has been observed only once and larger periods never at Vilsandi. This feature eventually reflects specific features of visual observations. They tend to over-estimate the proportion of windseas [31] and systematically underestimate the peak periods by a few tenths of seconds [29,30]. The Almagrundet data indicate

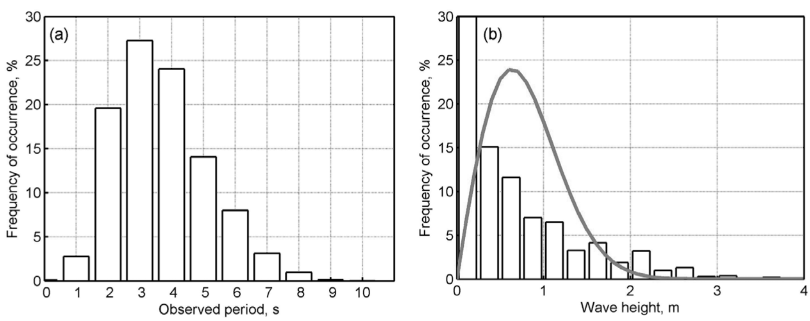

Fig. 5. Distribution of the occurrence of different wave periods (a) and daily mean wave heights (b) at Vilsandi. Notice that panel (a) reflects wave conditions only with non-zero periods, that is, the calm seas are excluded, whereas panel (b) reflects also observed calm conditions. The solid line in panel (b) reflects the corresponding Rayleigh distribution.

that long waves with periods over 10 s usually correspond to low swell conditions when the wave height is well below 1 m. Such waves are not easy to detect from the coast.

Figure 4 suggests that the wave heights in very rough seas (in particular, unrealistically high waves with the height over 4 m) are probably overestimated or reflect groups of large breaking waves. They may also represent a superposition of the incoming and reflected waves, or some specific cross-seas conditions. It is improbable that such combinations of wave heights and periods may occur at the open sea because typical periods in the wave conditions in question range from 5 to 9 s and mostly are from 6 to 8 s. They are much smaller than typical wave periods in extremely rough seas in the Baltic Proper [1,16].

The maximum (mean) wave height was reported to exceed 4.5 m (4 m) several times. There are 26, 9, 6 and 8 observations of wave heights over 4 m in 1954–1957, respectively. The diaries report 8 m high single waves in 5 observations on 17 and 28 September 1954 and on 15–16 October 1955. A wave height of 6.5 m is reported on 9 January 1954 and a 6 m high wave on 31 August 1956. Starting from 1958, the observed maximum (mean) wave height never exceeded 5 m (4 m). Five metres high single waves are once reported in 1997 and once in 2000. Since all the described observations were made in quite strong wind conditions and the maximum and mean wave heights were in a reasonable balance, they eventually correspond to a certain overestimation of wave parameters in relatively rough seas in the early years of the observations.

As a first approximation, the observations of over 4.5 m high single waves (51 observations) were corrected to physically reasonable 4.5 m, and observations of over 4 m high mean wave heights (34 observations) to 4 m. The difference of the mean and maximum wave heights was kept 0.5 m in such cases in order to match the average ratio of 0.94 of these measures. The listed values also roughly match the relevant wave periods in other cases of very rough seas (Fig. 4). The number of corrected entries is about 0.1% from the total number of sensible observations (Table 1). The potential errors of the average wave properties are small; for example, the overall average of maximum wave heights decreases less than 0.2% after the correction. Further analysis has been performed with the use of the corrected wave heights.

5. DISTRIBUTIONS OF WAVE HEIGHTS AND PERIODS

The average wave height at different observation times varies significantly (Table 1). This variation obviously has its origin in the seasonal course of the wave conditions. Statistically, rough seas occur more often in late autumn and winter when only the noon observation can be made in daylight. Therefore the straightforward use of the set of the observations would result in a certain bias of the mean wave properties. For that reason, further analysis relies on the daily average wave height, calculated as an arithmetic mean of sensible observations of each day.

The average wave height at Vilsandi, calculated from daily mean wave heights, is 0.575 m. This is clearly smaller than the mean significant wave height at Almagrundet (0.876 m in 1978–1995 and 1.04 m in 1993–2003 [16]). The wave height median is 0.3 m that is also much smaller than at Almagrundet.

A large part of these differences is apparently caused by the specific location of the observation site. A very rough estimate of the open sea wave climate, based on the Vilsandi data, can be made using the wave statistics from the open part of the Baltic Proper. The fraction of calm situations (wave height less than 0.25 m) is about 5–7% in the northern Baltic Proper [1] but it is much higher in the Vilsandi data. The excess proportion of calm days evidently is largely due to the absence of observable waves in many cases of easterly winds. Removing a fraction of calm days from the Vilsandi data set is therefore roughly equivalent to ignoring such wind conditions. If the number of calm records is reduced to 6% from the total number of non-zero wave conditions, the average wave height at Vilsandi would be 0.74 m and the wave height median close to 0.5 m. These estimates match much better wave conditions at Almagrundet. Note that such an ignoring of a part of calm conditions (equivalently, waves created by easterly winds) insignificantly affects the distribution of relatively rough wave conditions, because easterly winds usually are weak in this area [32]. The relevant correction coefficient for the above estimates of the long-term properties of wave fields is about 1.28.

The probability distribution of the occurrence of different wave heights (Fig. 5b) resembles analogous distributions of wave heights in semi-sheltered bays of the Baltic Sea [17]. It is largely different from the analogous distribution at Almagrundet that resembles the Rayleigh distribution [16]. The probability of the occurrence of the wave height $H \geq 4$ m is about 0.2% that well matches the analogous probability for $H_{1/3} \geq 4$ m (about 0.42%) at Almagrundet in 1978–2003. Yet these estimates are not directly comparable, because a part of observations of over 4 m high waves from the first years of wave observations at Vilsandi may be overestimated and extremely rough wave conditions that occur during a short time in the Baltic Proper may be undersampled in the Vilsandi data.

6. SEASONAL VARIATIONS AND LONG-TERM TRENDS OF WAVE HEIGHTS

The observed wave conditions exhibit a strong seasonal variability at Vilsandi (Fig. 6a). The monthly mean wave height varies from about 0.4 m during the summer to about 0.8 m in the winter. The highest wave activity occurs in January but from October to December a comparable wave activity is observed. The calmest months are the spring and summer months from March to August, with a well-defined minimum in May. Such an annual variation mostly matches the annual variation of the wind speed in the northern Baltic Proper [21]. It also

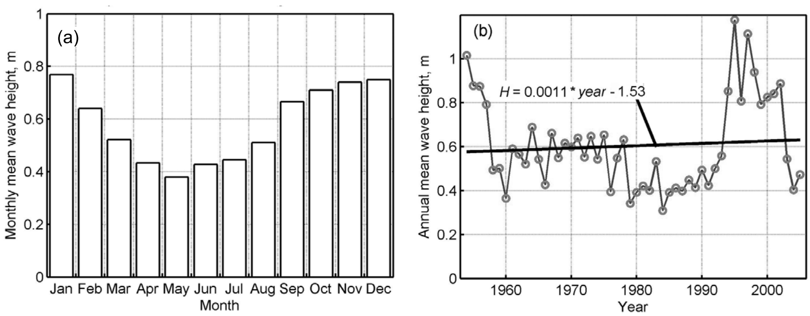

Fig. 6. (a) Seasonal variation of the monthly mean wave height at Vilsandi; (b) annual mean wave height at Vilsandi in 1954–2005.

resembles the similar cycle of water level at this site [39]. The two cycles are only shifted by 1–2 months with respect to each other. The seasonal variation of the wave height at Vilsandi is somewhat less pronounced than at Almagrundet, where the mean wave heights at the most rough and at the calmest months differ from 2.2 to 2.6 times [16]. This difference may reflect different measurement procedures but most probably it reflects the above-discussed absence of waves, excited by eastern winds at Vilsandi.

The total coverage of the measurements is 52 years. This time interval is long enough to extract long-term features of the changes in the overall wave activity. Figure 6b presents the annual mean wave height, calculated from the daily mean heights. The wave heights in the first four years of observations (1954–1957) may be overestimated, because most of the unrealistically high waves were observed during these years. However, the qualitative behaviour of the mean wave height in 1954–1957 apparently reflects a decrease of the wave activity during these years.

The most important conclusion from Fig. 6b is that no simple trend exists in the long-term variation of the annual mean wave height at Vilsandi. The formal trend is indistinct, about 0.1% per annum. The correlation coefficient between the linear trend and the mean wave height is fairly small ($R^2 \cong 0.0063$). Instead, a quasiperiodic variation of the overall wave activity can be distinguished. The interval between subsequent time periods of high or low wave activity is about 25 years. The wave heights are relatively large in 1965–1975 and at the end of the 1990s. The latter maximum is much more pronounced than the former one. The wave activity decreases fast starting from the end of the 1990s. The sea was comparatively calm in the end of the 1950s and in the middle of the 1980s.

The Almagrundet data from the turn of the century were considered as doubtful in [16]. It was argued that the large variation of the wave heights in 1995–2003 did not match the analogous variation of the annual and monthly mean wind speed at Utö, although the wind data from this small island in the northern Baltic

Proper (Fig. 1) represents well the open-sea wind conditions [1,22]. Comparison of Fig. 6b with Fig. 8 of [16] shows that the Almagrundet data from 1995–2003 are in good agreement with the Vilsandi data. Consequently, both data sets probably reflect the changing wave situation in these years.

A fast increase in the annual mean wave height at Vilsandi occurred in 1979–1995. The increase rate is as high as 2.8% per annum, with a reasonably high correlation coefficient $R^2 = 0.44$. This trend follows the increase of the annual mean wave height at Almagrundet as well as analogous trends for the southern Baltic Sea, the North Sea and for the North Atlantic [30,40–42]. It also matches the general tendency of the wind speed to increase over the northern Baltic Sea [16]. Yet this trend existed only during 1.5–2 decades and has been replaced by a decrease of the overall wave activity at the end of the century.

7. CONCLUSIONS AND DISCUSSION

The data set of visual wave observations at Vilsandi cannot be used as an adequate approximation of the time series of the sea state because of their low temporal resolution. Yet the performed analysis suggests that the data represent well general features of the Baltic Sea wave fields, extracted from other data sets. They apparently reflect the basic properties of the wave climate in this area such as a relatively low overall wave activity, short wave periods, and a substantial seasonal variation of the wave conditions that mostly match an analogous variation of the monthly mean sea level.

The central and somewhat surprising outcome from the Vilsandi data is that no clear trend of increasing wave activity can be identified in the northern Baltic Proper. This conclusion is supported by the match of the long-term behaviour of the annual mean wave height at Almagrundet and at Vilsandi. The wave activity at both sites considerably increased in the 1980s, was the highest at the turn of the century and is quickly decreasing starting from about 1998 [16].

Both the temporal behaviour of the wave activity and the water level usually reflect certain features of the wind impact. Somewhat counter-intuitively, the long-term behaviour of the mean wave height does not match the behaviour of the annual amplitude of the monthly mean sea level at the Finnish coast. This amplitude drastically increased in the 1970s and 1980s, and decreased again at the end of the 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 [43].

The average wave height not necessarily exactly follows the temporal behaviour of the mean wind speed. Yet it is intuitively clear that a larger wind speed generally causes a greater wave activity. This feature eventually causes the similarity of the seasonal cycles of the monthly mean wind speed and the wave height. The match of the temporal behaviour of the Utö wind data and the wave data from Almagrundet in 1979–1995 exists even in years, poorly covered by wave measurements. Quite surprisingly, the rapidly falling trend of the annual average wave height both at Almagrundet and at Vilsandi after 1998 does not match the relevant Utö wind data (see Figs. 8 and 9 in [16]).

The mismatch of the changes of the wind and wave properties in the northern Baltic Proper is a highly interesting feature and needs further investigation. It was hypothesized in [16] that secular changes in the dominating wind directions may affect the trends of Almagrundet wave heights. The qualitative match of the long-term variation of wave properties at the opposite coasts, however, suggests that this is unlikely. Consequently, changes 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 [3,44] may play an important role in the forming of the long-term variations of the Baltic Sea wave fields.

ACKNOWLEDGEMENTS

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REFERENCES

1. Kahma, K., Pettersson, H. and Tuomi, L. Scatter diagram wave statistics from the northern Baltic Sea. *MERI – Report Series of the Finnish Institute of Marine Research*, 2003, **49**, 15–32.
2. Soomere, T., Behrens, A., Tuomi, L. and Nielsen, J. W. Unusual wave conditions in the northern Baltic Sea during windstorm Gudrun in January 2005. *Geophys. Res. Abstr.*, 2006, **8**, Paper 02851.
3. Suursaar, Ü., Kullas, K., Otsmann, M., Saaremäe, I., Kuik, J. and Merilain, M. Hurricane Gudrun and modelling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Env. Res.*, 2006, **11**, 143–159.
4. Orviku, K., Jaagus, J., Kont, A., Ratas, U. and Rivis, R. Increasing activity of coastal processes associated with climate change in Estonia. *J. Coastal Res.*, 2003, **19**, 364–375.

5. WASA Group. The WASA project: changing storm and wave climate in the northeast Atlantic and adjacent seas? GKSS Report 96/E/61, Geesthacht, 1995.
6. Mietus, M. and von Storch, H. Reconstruction of the wave climate in the Proper Baltic Basin, April 1947–March 1988. GKSS Report 97/E/28, Geesthacht, 1997.
7. Sterl, A. and Caires, S. Climatology, variability and extrema of ocean waves – the web-based KNMI/ERA-40 wave atlas. *Int. J. Climatol.*, 2005, **25**, 7, 963–977.
8. Pettersson, H. Directional wave statistics from the southern Bothnian Sea 1992. Internal report 5/1994, Finnish Institute of Marine Research, Helsinki, 1994.
9. Kahma, K., Rantanen, E. and Saarinen, J. Wave data from the southern Bothnian Sea 1973–1975, 1981. Internal report 1/1983, Finnish Institute of Marine Research, Helsinki, 1983.
10. Kahma, K. and Pettersson, H. Wave statistics from the Gulf of Finland. Internal report 1/1993, Finnish Institute of Marine Research, Helsinki, 1993.
11. Kahma, K. and Pettersson, H. Wave growth in a narrow fetch geometry. *The Global Atmosphere and Ocean System*, 1994, **2**, 253–263.
12. Pettersson, H. Directional wave statistics from the Gulf of Finland 1990–1994. *MERI – Report Series of the Finnish Institute of Marine Research*, 2001, **44**, 1–37.
13. Pettersson, H. *Wave Growth in a Narrow Bay*. PhD Thesis. Finnish Institute of Marine Research, Contributions No. 9, Helsinki, 2004.
14. *Guide to the Applications of Marine Climatology*. WMO Publication 781, Geneva, 2001.
15. Mårtensson, N. and Bergdahl, L. On the wave climate of the Southern Baltic. Report Series A:15, Department of Hydraulics, Chalmers University of Technology, Göteborg, 1987.
16. Broman, B., Hammarklint, T., Rannat, K., Soomere, T. and Valdmann, A. Trends and extremes of wave fields in the north-eastern part of the Baltic Proper. *Oceanologia*, 2006, **48**(S), 165–184.
17. Soomere, T. Wind wave statistics in Tallinn Bay. *Boreal Env. Res.*, 2005, **10**, 103–118.
18. Soomere, T. Unique wave conditions in the Baltic Sea in January 2005. *Publicationes Geophysicales Universitatis Tartuensis*, 2006, **50**, 215–224.
19. Rzheplinskij, G. V. (ed.). *Wave and Wind Atlas for the Baltic Sea*. Tallinn, 1965 (in Russian).
20. Davidan, I. N., Lopatoukhin, L. I. and Rozhkov, V. A. *Wind Waves in the World Oceans*. Gidrometeoizdat, Leningrad, 1985 (in Russian).
21. Mietus, M. (coordinator). The climate of the Baltic Sea Basin, Marine meteorology and related oceanographic activities. Report No. 41, World Meteorological Organisation, Geneva, 1998.
22. Soomere, T. Anisotropy of wind and wave regimes in the Baltic Proper. *J. Sea Res.*, 2003, **49**, 305–316.
23. Jönsson, A., Broman, B. and Rahm, L. Variations in the Baltic Sea wave fields. *Ocean Eng.*, 2002, **30**, 107–126.
24. Jönsson, A., Danielsson, A. and Rahm, L. Bottom type distribution based on wave friction velocity in the Baltic Sea. *Continental Shelf Res.*, 2005, **25**, 419–435.
25. Gayer, G., Günther, H. and Winkel, N. Wave climatology and extreme value analysis for the Baltic Sea area off the Warnemünde harbour entrance. *Deutsche Hydrogr. Zeitschr.*, 1995, **47**, 109–130.
26. Paplińska, B. Wave analysis at Lubiatowo and in the Pomeranian Bay based on measurements from 1997/1998 – comparison with modelled data (WAM4 model). *Oceanologia*, 1999, **41**, 241–254.
27. Blomgren, S., Larsson, M. and Hanson, H. Numerical modelling of the wave climate in the southern Baltic Sea. *J. Coastal Res.*, 2001, **17**, 342–352.
28. Hogben, N., Da Cunha, N. M. C. and Oliver, G. F. *Global Wave Statistics*. Unwin Brothers, London, 1986.
29. Gulev, S. K. and Hasse, L. North Atlantic wind waves and wind stress fields from voluntary observing ship data. *J. Phys. Oceanogr.*, 1998, **28**, 1107–1130.
30. Gulev, S. K. and Hasse, L. Changes of wind waves in the North Atlantic over the last 30 years. *Int. J. Climatol.*, 1999, **19**, 1091–1117.

31. Orlenko, L. R., Lopatukhin, L. I. and Portnova, G. L. (eds.). *Studies of the Hydrometeorological Regime of Tallinn Bay*, Gidrometeoizdat, Leningrad, 1984 (in Russian).
32. Soomere, T. and Keevallik, S. Anisotropy of moderate and strong winds in the Baltic Proper. *Proc. Estonian Acad. Sci. Eng*., 2001, **7**, 35–49.
33. Zaitseva, I. Lainetuse statistikast Eesti rannikuvetes visuaalsete vaatluste alusel. Manuscript, Eesti Mereakadeemia, Tallinn, 2006.
34. *Vilsandi Meteoroloogia-hüdroloogiajaama Tehniline Teatmik*. Eesti Meteoroloogia ja Hüdroloogia Instituut, Tallinn, 1968.
35. *Guidelines for Hydrometeorological Stations and Posts. Issue 3, Part 1. Meteorological Observations at Stations*. Gidrometeoizdat, Leningrad, 1985 (in Russian).
36. Soomere, T. Wave regimes and anomalies off north-western Saaremaa Island. *Proc. Estonian Acad. Sci. Eng.*, 2001, **7**, 157–173.
37. IAHR working group on wave generation and analysis. List of sea-state parameters. *J. Waterw. Port Coast. Ocean Eng.*, 1989, **115**, 793–808.
38. Massel, S. R. *Hydrodynamics of Coastal Zones*. Elsevier, Amsterdam, 1989.
39. Õmblus, A. Läänemere veetaseme aastase muutlikkuse käik ja hinnang amplituudile. MSc thesis. Tartu Ülikool, Tartu, 2005.
40. Vikebo, F., Furevik, T., Furnes, G., Kvamsto, N. G. and Reistad, M. Wave height variations in the North Sea and on the Norwegian Continental Shelf 1881–1999. *Continental Shelf Res.*, 2003, **23**, 251–263.
41. Bacon, S. and Carter, D. J. T. The wave climate changes in the North-Atlantic and North Sea. *Int. J. Climatol*., 1991, **11**, 545–558.
42. Kushnir, Y., Cardone, V. J., Greenwood, J. G. and Cane, M. A. The recent increase of North Atlantic wave heights. *J. Clim*., 1997, **10**, 2107–2113.
43. Johansson, M., Boman, H., Kahma, K. K. and Launiainen, J. Trends in sea level variability in the Baltic Sea. *Boreal Environ. Res.*, 2001, **6**, 159–179.
44. Alexandersson, H., Schmith, T., Iden, K. and Tuomenvirta, H. Long-term variations of the storm climate over NW Europe. *The Global Atmosphere and Ocean System*, 1998, **6**, 97–120.

Läänemere põhjaosa lainekliima hinnang Vilsandil tehtud visuaalsete vaatluste alusel

Tarmo Soomere ja Inga Zaitseva

On analüüsitud Läänemere avaosa põhjapoolse sektori lainekliima põhilisi parameetreid ja lainekõrguse sesoonset ning pikaajalist muutlikkust Vilsandil aastail 1954–2005 visuaalselt hinnatud lainetuse omaduste alusel. Lainete tüüpilised perioodid on 2–4 s. Kuu keskmise lainekõrguse aastane varieerumine on analoogiline tuulekiiruse varieerumisega. Kuu keskmine lainekõrgus on väikseim, ligikaudu 0,4 m, aprillist juulini, kuid ulatub 0,8 meetrini jaanuaris. Aasta keskmine lainekõrgus muutus suhteliselt vähe 1960. ja 1970. aastatel, kuid suurenes oluliselt 1980. aastatel, saavutas viimase poole sajandi maksimumi 1990. aastate teisel poolel ja on kiiresti kahanenud alates 1998. aastast.

Paper II

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Seasonal and Long-term Variations of Wave Conditions in the Northern Baltic Sea

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ABSTRACT

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Although the Baltic Sea is a relatively small water body, it may host significant wave heights up to 9–10 m. Several authors claim that the rough seas have already caused extensive erosion of depositional coasts of this body of water. We make an attempt to merge historical visual observations and numerical hindcasts to reveal the basic features of the wave properties. Wave conditions, their seasonal cycle, and inter-annual and long-term variations in the northern part of the Baltic Sea are studied based on (i) visual observations along its eastern coast at Vilsandi (1954–2005) and at Pakri (1954–1985), (ii) instrumentally measured wave properties at Almagrundet (1978–2003) on the western coast, (iii) directional wave statistics from the northern Baltic Proper (1996–2002), and (iv) wave hindcast near Saaremaa using a point model. The typical wave periods are 4–6 s and in coastal areas 2–4 s. The monthly mean wave height follows the seasonal variation in wind speed with a maximum in October–January. The observed annual mean wave height reveals nearly synchronous, substantial decadal-scale variations in the entire region, and a rapid increase (1–2% annually) until the mid-1990s. The increasing trend was replaced by a decrease of the mean wave height since 1997, although the mean wind speed continues to increase over the area. The model qualitatively represents the long-term variations of the wave intensity.

ADDITIONAL INDEX WORDS: *Wave climate, wave modeling, trends, climate change, Baltic Sea.*

INTRODUCTION

Studies concerning properties of complex wave fields in different sea areas and research towards the understanding of both the status and changes of the wave climate undoubtedly form one of the key elements of contemporary physical oceanography and coastal science. This is not only because surface waves are a major driver of processes in the surface layer, nearshore, and coastal area, but also because the wave climate is one of the most sensitive indicators of the changes in wind regime and local climate in semi-enclosed sea areas.

The complexity of physics and dynamics of the Baltic Sea extend far beyond the typical features of many other water bodies of comparable size (WULFF *et al*., 2001; BACC, 2008). This water body is characterized by extremely complex geometry, highly varying wind fields, extremely rough wave conditions at times, extensive archipelago areas with specific wave propagation properties, and ice cover during a large part of each year. The combination of a relatively small size and vulnerability of its ecosystem makes this region particularly susceptible 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 decades (BACC, 2008). There is evidence that the increasing storminess in this region starting in the 1970s has already caused extensive erosion of the depositional coasts (ORVIKU *et al*., 2003). This trend, however, has been severely questioned by many authors. The changes in the wave climate of some parts of the region have been found to be marginal, at least, until the mid-1990s (WASA GROUP, 1995; MIETUS and VON STORCH, 1997). The intensity and duration of severe wavestorms in the southern North Sea have decreased since about 1990–1995 (WEISSE and GÜNTHER, 2007). This decrease is consistent with the updated trends of storminess (ALEXANDERSSON *et al*., 2000).

Very rough seas measured twice in December 1999 (KAHMA *et al*., 2003) reinforced the discussion as to whether the wave conditions in the Baltic Sea have become rougher compared with the situation from a few decades ago. One exceptional storm, 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).

Recognition of the wave climate changes, and, 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 (1957–2002, 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°×1.5° areas. This resolution is too coarse for the Baltic Sea conditions.

We make an attempt to merge historical visual observations and numerical hindcasts to reveal the seasonal, annual, and decadal changes in the basic wave properties in the northern part of the Baltic Sea. As contemporary wave measurements are relatively scarce and short here, the reliable estimates of the wave climate

Figure 1. Location scheme of the long-term wave measurement and observation points, and points used for comparisons of modeled and measured data in the Baltic Sea.

require a combination of different data sources with extensive modeling resources. The analysis below is based on (i) visual observations at Vilsandi in 1954–2005 (SOOMERE and ZAITSEVA, 2007) and at Pakri in 1954–1985, (ii) instrumental measurements at Almagrundet (1978–2003) on the western coast of the Baltic Proper (BROMAN *et al*., 2006), (iii) directional wave statistics from the northern Baltic Proper in 1996–2002 (KAHMA *et al*., 2003), and (iv) wave hindcast for the Vilsandi observation point using a point model forced by high-quality marine winds (Figure 1).

METHODS AND DATA

The data from Almagrundet (1978–2003, 59°09' N, 19°08' E, Figure 1, BROMAN *et al*., 2006) form the longest and one of the most valuable instrumentally measured wave data sets in this region. The measurement site is at a 14 m deep shoaling area about 10 nautical miles south-east of Sandhamn in the Stockholm archipelago. The fetch for winds from the SW, W, and NW is quite limited at this site. The measurements were performed with the use of upward-looking echo-sounders placed at a depth of about 30 m. The position of the water surface was sampled over 640 seconds each hour. Single waves were identified based on the zero-downcrossing method. An estimate of the significant wave height H_S was found from the 10^{th} highest wave in a record under the assumption that wave heights are Rayleigh distributed. The set of 95,458 measurements from 1978–1995 reliably describes the wave properties. Later, 46,671 recordings taken from 1993–2003 have certain quality problems: the overall behavior of the wave height follows the sea state, but the periods are not usable (BROMAN *et al*., 2006), and they are not employed below.

A directional waverider has been operated by the Finnish Institute of Marine Research in the northern Baltic Proper at a depth of about 100 m (buoy 1 in Figure 1, 59°15´N, 21°00´E) since September 1996 during the ice-free seasons (KAHMA *et al*., 2003). This device, as well as contemporary spectral wave models, estimate the significant wave height as the four-fold 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 open Baltic Sea wave fields. However, to date, this time series is not long enough for determining the climatological values of wave properties.

A coastal site reasonably reflecting the open sea wave conditions for the dominant wind directions in the northern Baltic Proper is located at the Island of Vilsandi (58°22´59´´N, 21°48´55´´E, Figure 1) and is operated by the Estonian Meteorological and Hydrological Institute. This site gives inadequate data only for easterly winds which are relatively weak and infrequent in this area. Wave observations were made starting from 1954 up to three times a day, there. The observer noted the five highest waves during a 5-minute time interval and recorded the highest single wave and the mean height of these waves at Vilsandi. Given the typical wave periods in the coastal zone 3–4 s (BROMAN *et al*., 2006), the observed highest single wave height is approximately equal to the average height of 2.5–3 % of the highest waves. As the observers' estimates represent the significant wave height well (GULEV and HASSE, 1999), the visually observed data are interpreted as estimates of the significant wave height. The data represents the general features of the Baltic Sea wave fields well: relatively low overall wave activity, short wave periods, and substantial seasonal variation of wave conditions (SOOMERE and ZAITSEVA, 2007; SOOMERE, 2008).

The wave period was found as an arithmetic mean of three consecutive observations of the time for 10 waves to pass. 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. 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.

Another observation site where observed wave properties reasonably represent the open sea conditions is at Pakri in the western part of the Gulf of Finland (59°23´37´´N, 24°02´40´´E, Figure 1). Pakri is the only wave observation site on the southern coast of this gulf that is largely open to waves generated in the Baltic Proper. The average depth of the area over which the waves were observed was 8–11 meters. The procedure of wave observations was identical to the one used at Vilsandi. Waves were observed from a steep, >20 m high cliff, 24 m from the mean sea level. Regular wave observations are available from 1954. The recently digitized data set is discussed here for the first time. Unfortunately, this data set covers only 32 years up to 1985. The total number of records is 13,916. At least one sensible observation exists on 9,170 days from a total of 11,657 days.

The calculation of wave parameters near the Harilaid Peninsula was based on the fetch-limited equations of Sverdrup, Munk, and Bretschneider (SMB-model, see e.g. SEYMOUR, 1977; HUTTULA, 1994). Also called the significant wave method, the model is forced by wind speed data, effective fetch and water depth and it calculates the significant wave height, wave period and wavelength for the chosen location. The effective fetch is the distance over which the wind blows. It can be calculated from the wind direction as the headwind distance for the nearest shore point. In shallow, nearshore areas with complex shoreline geometry and bottom topography, long-term hindcast simulations with more up-to-date wave models may be time-consuming and complicated. In such conditions, fetch-limited point models may offer a simple alternative (ÖZGER and SEN, 2007). Among other tasks, we were interested in wave forcing conditions near the geomorphically interesting accumulative Kelba Spit of the Harilaid Peninsula (SUURSAAR *et al*., 2008).

The chosen location for hydrodynamic measurements and modeling was 1–1.5 km off the coast. For meteorological forcing of the SMB wave model, we used wind data from the Vilsandi meteorological station, which is the most open among the Estonian stations and located just 7 km south of the Harilaid (Figure 1). The data was available in digital form for the period 1966–2006. The wind has been measured with wind vanes from 1966–1976, with automatic anemorhumbometers from 1976 to 2003, and with MILOS-520 automatic weather complexes starting from September 2003. The older data in the database has been slightly corrected for homogeneity. The time interval was 3 hours from January 1966 to August 2003. MILOS provides hourly average wind speed and gust wind speed with the value step of 0.1 m/s, and hourly prevailing wind direction with a resolution of 1º.

For comparison and calibration of the SMB-model, an self-contained oceanographic measuring complex RDCP-600 (Aanderaa Data Instruments) was deployed to the seabed at the same location (58°28'N, 21°49'E) for which the wave calculations were made. The mooring depth was about 14 m. The upward looking instrument recorded from 20 December 2006 to 23 May 2007.

RESULTS

During the 5-month calibration period, the SMB model slightly underestimated the measured waves. In order to achieve the best fit of statistical parameters between the measured and modeled data sets, the model output was slightly corrected using a fourth-order polynomial, which produced both high correlation coefficient (0.880), low RMSE (0.233) and nearly equal RDCP average and maximum values (Figure 2). The same settings were further used in the 1966–2006 wave hindcast, presented in this study (Figure 3).

Although the Pakri observation site is sheltered from a part of the dominant SW winds, wave properties at this site mostly match the ones observed, measured or hindcast for the northern Baltic Proper. The distribution of the occurrence of wave height and mean periods at Pakri (Figure 4) reflects sensible wave observations with non-zero wave periods. This distribution has a shape typical for the Baltic Sea region (KAHMA *et al*., 2003). The most frequent wave periods are 2–3 s. The total mean wave height (calculated based on daily mean wave heights (SOOMERE and ZAITSEVA, 2007)) over all 32 years is 0.59 m. The average mean value of the recorded maximum wave heights is 0.61 m.

All the observed and hindcast data sets reproduce the basic features of the northern Baltic Sea wave fields (SOOMERE, 2008) such as (i) the overall mild wave regime in the basin, with the overall mean wave height in the open sea approximately 1 m and in the coastal areas 50–60 cm, (ii) a large proportion of wave conditions with the significant wave heights around 0.5 m (Figure 3), and (iii) the most frequent peak periods 4–6 s in the open sea and 2–4 s in the nearshore regions (Figure 4). All the listed values are characteristic to relatively small or semi-sheltered basins and are several times smaller than the similar values for the open ocean.

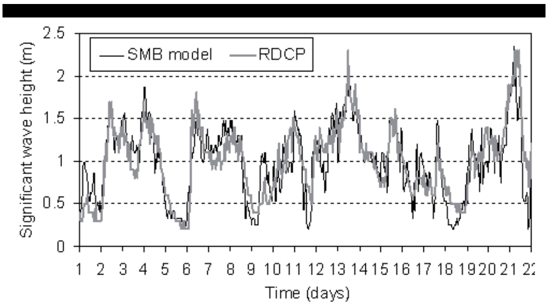

Figure 2. Measured (RDCP) and modeled significant wave height for the period of 21 December 2006 – 10 January 2007.

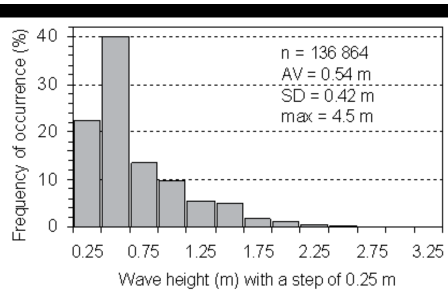

Figure 3. Frequency of occurrence of significant wave heights in hindcast data in 1966–2006.

A few (about 50 from total >32,000 recordings) recorded wave heights over 4 m were interpreted as erroneous at Vilsandi. The water depth in the observation area is about 4 m, but quite high single wave crests may at times occur owing to different shallow-water effects. Their properties may be filed by the observer because of the short observation period, but they do not adequately represent the open sea wave fields. Much higher waves, however, may occur at Pakri. The data set contains 6 cases when a maximum wave height of ≥5 m was recorded. These cases evidently correspond to realistic wave conditions in rough seas. The highest waves (6 m) were recorded in all available observations (twice each day) on 6–7 August 1967 when a strong NW storm excited extremely rough wave conditions and caused extensive damage to the forests. Waves with height of 5 m were recorded on 21 January 1964 and on 23 September 1969.

All data sets also reveal strong seasonal variability of the Baltic Sea wave fields (Figure 5). The amplitude of the seasonal cycle is quite large, for example, for the monthly mean wave heights it is up to ±40% from the annual mean value. The calmest months are April–June and the largest wave intensity can be found from October–January. The monthly mean wave height at Vilsandi varies from 0.4 m during summer to 0.8 m in winter. The seasonal cycle is also clearly visible in the most typical wave conditions, dominant wave periods, and higher percentiles of observed, measured, and hindcast wave heights. The seasonal cycle basically follows the annual variation of the wind speed in the northern Baltic Proper (MIETUS, 1998), which obviously mirrors the analogous cycle in cyclone generation over the North Atlantic.

Although Pakri is sheltered from some of the waves excited by the most frequent (SW) winds, the overall mean wave height at

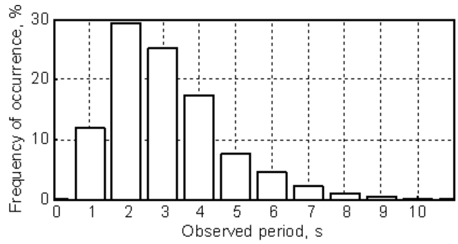

Figure 4. Frequency of occurrence of mean periods at Pakri.

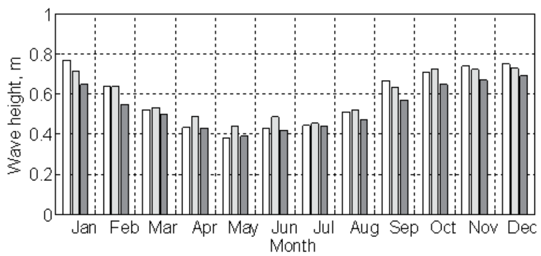

Figure 5. The monthly mean wave height at Vilsandi (white), at Pakri (light grey) and at Harilaid (dark grey).

Pakri and its seasonal variation almost exactly coincide with those at Vilsandi. This feature suggests that Pakri wave data also adequately represents the wave conditions in the open sea.

The overall course of wave activity (Figure 6) reveals no clear, long-term trend at Vilsandi and Pakri. Instead, a quasiperiodic variation can be identified for all the data sets. 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 then calmer again at the end of the 1970s. A rapid increase in the annual mean wave height occurred from the mid-1980s to the mid-1990s. The increase was well over 1% per annum depending on the particular choice of the time interval and the site (Almagrundet 1979–92: 1.3%; 1979–95: 1.8% (BROMAN *et al*., 2006); Vilsandi 1979–95 as high as 2.8 % per annum (SOOMERE and ZAITSEVA, 2007)). This trend follows the analogous trends for the southern Baltic Sea and for the North Atlantic (GULEV and HASSE, 1999; WEISSE and GÜNTHER, 2007). 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 occurring in the 20th century over most of the North Atlantic and northern Europe (ALEXANDERSSON *et al*., 2000).

This trend only existed for about 1.5 decades and was replaced by a drastic decrease in the mean wave height since 1997. The relevant data from Almagrundet was even estimated as doubtful by BROMAN *et al*. (2006) because the annual mean wind speed in the northern Baltic Proper continued to increase, as suggested by data from the island of Utö (Figure 1). 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.

Variations of the annual mean wave height at Pakri are the most similar to those at Vilsandi (Figure 6). The largest difference is in

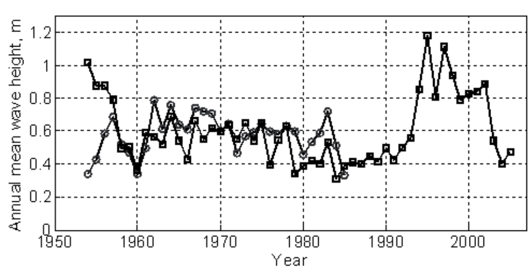

Figure 6. The annual mean wave height at Vilsandi (squares) and Pakri (circles, 1954–1985).

the data from first three years of visual observations (1954–1956) during which apparently wave properties have been overestimated at Vilsandi (SOOMERE and ZAITSEVA, 2007). There is an increase in the mean wave height at Vilsandi and for a few years at Pakri and Harilaid around the year 1960, and an overall slow decrease until the the mid-1970s. The almost perfect match of short-term variability (1–3 years) of the annual mean wave heights and a high correlation coefficient (0.58) between these values in 1957–1985 at Vilsandi and Pakri once more confirms that the visual wave observations reproduce the basic properties of wave fields and their changes. Although the Pakri data exist only until 1985, still the above discussion suggests that the drastic variations of wave properties at Vilsandi reflect real changes in wave fields in the Baltic Proper even if they are not reproduced by models.

Near the Harilaid Peninsula, the results on long-term variations of averages (Figure 7) showed quasi-periodic 30–40 year cycles with above-average values roughly from 1980–1995, and lower values from 1970–1980 and up until 1995. The overall trend of averages was negative with an average slope of –0.001 m per annum (or –4.2 cm over the 41 year period).

According to this data set, the highest wave storm (HS about 4.5 m) probably occurred on 2 November 1969, when wind with sustained speed of 24 m/s, blew from the direction of 290º (W–NW). The second highest event occurred on 9 January 2005 during the hurricane Gudrun (significant wave height 4.2 m, wind speed 23 m/s, 270º). However, due to malfunction of the equipment at Vilsandi station, the existing wind data (and therefore also wave hindcast) might be slightly underestimated. Probably the roughest wave conditions ever estimated for the Baltic Sea were associated with windstorm Gudrun in January 2005. Significant wave height, in this instance, probably reached 9.5 m and the peak wave period exceeded 12 s 10–30 km off the coast of NW Saaremaa (Soomere et al., 2008).

DISCUSSION

In the case of Harilaid data, the correlation coefficients between wave and wind statistics were rather high (0.86, both in average wind speed and westerly wind component) and the trends in wave

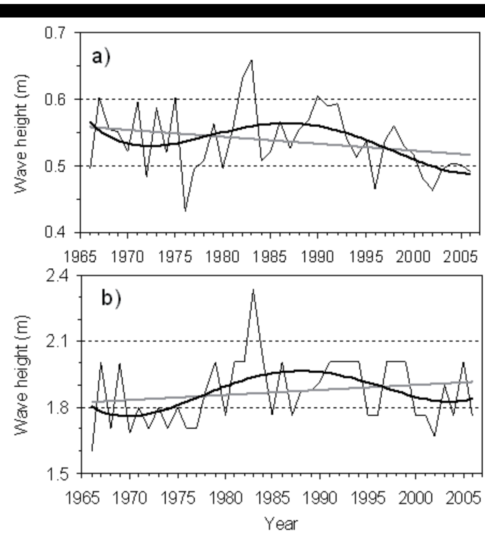

Figure 7. The annual average of significant wave height (a) and its annual 99% value (b) near Harilaid in 1966–2006.

parameters were quite similar to those in wind statistics. This is quite natural, as the SMB wave model is directly forced by the corresponding wind data. Still, the connection is not always straightforward due to the fetch-limited study area. For example, there were a number of strong windstorms in the record, which, due to unfavorable direction, did not yield equally prominent wave storms. Such storm events occurred, for example, on 12–13 March 1992, 27 February 1990, and 17 December 1999.

While the annual means of wave height at the two observation sites are highly correlated, the match between the modeled wave properties at Harilaid (Figure 7) and visually observed wave data at Vilsandi is far from perfect. Although a period of increase in modeled wave heights occurred in 1975–1993 with a subsequent decrease since 1998, the modeled data do show a large increase at the turn of millennium. This is not unexpected, because the model in use does not account for spatial variability of wind fields. Yet several aspects become evident from both data sets. The modeled data also do not reveal any distinct trend; instead, a quasi-periodic variation of the overall wave activity can be identified.

However, the series of 99% percentiles showed a clear increasing trend (Figure 7). This feature is particularly interesting, because it may be interpreted as evidence of an increase in the wave heights of extreme storms on the background of a decreasing trend of the overall wave activity (SOOMERE and HEALY, 2008).

CONCLUSIONS

The analyzed data sets represent the basic properties of the wave climate in the northern Baltic Sea. The typical wave periods are 4–6 s (2–4 s in coastal areas). The monthly mean wave height follows the seasonal variation in wind speed with a maximum in October–January and with the late spring and early summer months as the calmest. The annual mean wave height reveals nearly synchronous, substantial decadal-scale variations in the entire region, and a rapid increase of wave height (1–2% annually) until the mid-1990s. The increasing trend was replaced by a decrease in the mean wave height since 1997, although the mean wind speed continues to increase over the area. The models qualitatively represent these long-term variations. The presented features, in particular, the long-term changes, apparently are site-specific in the sense that they represent long-term changes in the storminess over the North Atlantic and related changes in the wind patterns over the Baltic Sea.

LITERATURE CITED

THE BACC AUTHOR TEAM, 2008. *Assessment of Climate Change for the Baltic Sea Basin*. Springer, Berlin, Heidelberg, 473 pp.

BROMAN, B.; HAMMARKLINT, T.; RANNAT, K.; SOOMERE, T., and VALDMANN, A., 2006. Trends and extremes of wave fields in the north–eastern part of the Baltic Proper. *Oceanologia*, 48 (S), 165–184.

ALEXANDERSSON, H.; TUOMENVIRTA, H.; SCHMITH, T., and IDEN, K., 2000. Trends of storms in NW Europe derived from an updated pressure data set. *Climate Researc*h, 14 (1), 71–73

GULEV, S. K. and HASSE, L., 1999. Changes of wind waves in the North Atlantic over the last 30 years. *International Journal of Climatology*, 19 (10), 1091–1117.

HUTTULA, T., 1994. Suspended sediment transport in Lake Säkylän Pyhäjärvi. *Aqua Fennica*, 24 (2), 171–185.

KAHMA, K.; PETTERSSON, H., and TUOMI, L., 2003. Scatter diagram wave statistics from the northern Baltic Sea. *MERI – Report Series of the Finnish Institute of Marine Research*, 49, 15–32.

KOMEN, G.J.; CAVALERI, L.; DONELAN, M.; HASSELMANN, K.; HASSELMANN, S., and JANSSEN, P.A.E.M., 1994. *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambridge.

MIETUS, M., 1998. The climate of the Baltic Sea Basin, Marine meteorology and related oceanographic activities. Report No. 41. World Meteorological Organization, Geneva.

MIETUS, M. and VON STORCH, H., 1997. Reconstruction of the wave climate in the Proper Baltic Basin, April 1947–March 1988, GKSS Report 97/E/28, Geesthacht.

ORVIKU, K.; JAAGUS, J.; KONT, A.; RATAS, U., and RIVIS, R., 2003. Increasing activity of coastal processes associated with climate change in Estonia, *Journal of Coastal Research*, 19 (2), 364–375.

ÖZGER, M. and SEN, Z., 2007. Triple diagram method for the prediction of wave height and period. *Ocean Engineering*, 34 (7), 1060–1068.

SEYMOUR, R.J., 1977. Estimating wave generation in restricted fetches. *J. ASME WW2, May 1977*, 251–263.

SOOMERE, T., 2008. Extremes and decadal variations of the northern Baltic Sea wave conditions. *Extreme Ocean Waves* (in Pelinovsky, E., Kharif, Ch., Eds.), Springer, 139–157.

SOOMERE, T. and HEALY, T., 2008. Escalating extremes over descending trends of the northern Baltic Sea wave fields, in: Wallendorf, L.; Ewing, L.; Jones, C., and Jaffe, B., (eds.), *Solutions to Coastal Disasters* 2008, American Society of Civil Engineers, pp. 129–138.

SOOMERE, T. and ZAITSEVA, I., 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proceedings of the Estonian Academy of Sciences, Engineering*, 13 (1), 48–64.

SOOMERE, T.; BEHRENS A.; TUOMI L., and NIELSEN J.W., 2008. Wave conditions in the Baltic Proper and in the Gulf of Finland during windstorm Gudrun. *Natural Hazards and Earth System Sciences*, 8 (1), 37–46.

STERL, A. and CAIRES, S., 2005. Climatology, variability and extrema of ocean waves – the web-based KNMI/ERA-40 wave atlas. *International Journal of Climatology*, 25, 963–977.

SUURSAAR, Ü.; JAAGUS, J.; KONT, A.; RIVIS, R., and TÕNISSON, H., 2008. Field observations on hydrodynamic and coastal geomorphic processes off Harilaid Peninsula (Baltic Sea) in winter and spring 2006–2007. *Estuarine Coastal and Shelf Science*, 80 (1), 31–41.

SUURSAAR, Ü.; KULLAS, T.; OTSMANN, M.; SAAREMÄE, I.; KUIK, J., and MERILAIN, M., 2006. Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Environment Research*, 11 (2), 143–159.

WASA GROUP, 1995. The WASA project: changing storm and wave climate in the northeast Atlantic and adjacent seas? *Proceedings of the Fourth International Workshop on Wave Hindcasting and Forecasting, Banff, Canada, October 16–20*, pp. 31–44; also: GKSS Report 96/E/61.

WEISSE, R. and GÜNTHER, H., 2007. Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958–2002. *Ocean Dynamics*, 57 (3) 161–172.

WULFF, F.V.; RAHM, L.A., and LARSSON, P., (eds.), 2001. *A systems analysis of the Baltic Sea*. Ecological Studies 148, Berlin: Springer, 430 pp.

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Paper III

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OCEANOGRAPHY

Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea

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Abstract. Visual wave observations from the north-eastern coast of the Baltic Proper and from the southern coast of the Gulf of Finland and numerically hindcast wave properties for the entire Baltic Sea were used for the identification of combinations of wave heights and periods in extreme storms and long-term changes in extreme wave heights and wave propagation directions. The extreme wave heights and periods are about 7 m and 10–12 s in the northern Baltic Proper, about 6 m and 8–11 s at the entrance to the Gulf of Finland, and about 4 m and 6–8 s in the eastern part of this gulf. Wave hindcasts show no statistically significant trends in the 95%-iles and 99%-iles of the wave heights. Significant observed changes in the directional distribution of waves at Narva-Jõesuu from the 1980s are not represented in hindcasts.

Key words: wave modelling, wind waves, Baltic Sea, climate change, visual wave observations.

1. INTRODUCTION

Studies of properties of complex wave fields in different sea areas and research towards understanding both the status of and changes in the wave climate form one of the key elements of physical oceanography and coastal science. This is not only because surface waves are a major driver of processes in the surface layer, nearshore, and coastal area, but also because the wave climate is one of the most robust indicators of changes in the wind regime in semi-enclosed sea areas. The potential for the increase in wave heights, for example, in the North Sea (18%) is substantially greater than that of the wind speed (7% for the 99%-iles; Grabemann and Weisse, 2008). An accurate picture of typical and extreme wave properties and their potential changes is, thus, of great value for a wide variety of research topics and engineering applications.

Research into long-term changes in wind properties over the Baltic Sea has highlighted greatly variable patterns of changes (Jaagus et al., 2008). The average wind speed has been increasing over most of this basin (Pryor and Barthelmie, 2003) while a decrease has been observed in a part of the West Estonian Archipelago and on the southern coast of the Gulf of Finland (Keevallik and Soomere, 2004; Kull, 2005). Storminess in the entire region gradually decreased over the first half of the 20th century and rapidly increased in the 1980s–1990s (Alexandersson et al., 1998), raising concerns about destructions to sedimentary coasts (Orviku et al., 2003). On the other hand, both the overall storminess and the number of storm days in the Finnish marine areas decreased since the mid-1990s (Alexandersson et al., 2000; Helminen, 2006).

Long-term changes in wave properties in water bodies adjacent to the Baltic Sea also reveal controversial patterns. Early reviews found an increase in the mean wave height over the whole of the North Atlantic and North Sea, possibly since 1950, of about 2%/year (Bacon and Carter, 1991, 1993). A statistical hindcast over the period of 1962–1986 revealed an increase in the significant wave height at several locations since about 1960 (Kushnir et al., 1997). Subsequent estimates concluded that the North Atlantic wave climate has under-

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gone significant decadal variations but revealed no clear trends (WASA Group, 1998) although there was an apparent artificial worsening of the storm climate in data-sparse areas (Günther et al., 1998). Wang and Swail (2002) argued that the north-east Atlantic has roughened in winters of the last four decades. Numerical reanalysis revealed that the number of rough wave conditions increased only in the 1960s–1970s, but both the intensity and duration of severe storms decreased in the 1990s (Weisse and Günther, 2007). A similar reduction was characteristic of the UK North Sea coast since the 1970s.

The existing long-term wave measurements, observations, and simulations from the Baltic Sea contribute to this pool of controversial patterns. Instrumental data from Almagrundet and visual data from Vilsandi suggest that during the 1980s there was a rapid increase in the annual mean wave activity in the northern Baltic Proper (nBP) (Broman et al., 2006; Soomere and Zaitseva, 2007), followed by a drastic decrease since 1997, and quite low average wave activity since about 2005 (Zaitseva-Pärnaste et al., 2009). At the same time in December 1999 extremely rough seas occurred in the Baltic Sea (Kahma et al., 2003), and windstorm Gudrun in January 2005 apparently caused the all-time highest significant wave height $H_S \approx 9.5$ m (Soomere et al., 2008). This raised the question as to whether the trends for average and extreme wave heights are different in the Baltic Sea basin (Soomere and Healy, 2008).

No such variation was found along the Lithuanian coast (Kelpšaite et al., 2008) and in the Gulf of Finland (GoF). Instead, a stable situation in wave heights was established for certain parts of this gulf (Kelpšaite et al., 2009). Numerical simulations failed to represent the above variations in the nBP (Räämet et al., 2009; Suursaar and Kullas, 2009; Zaitseva-Pärnaste et al., 2009) although they replicated a large part of the interannual variability of the wave fields. The discrepancies between the observed and modelled data apparently stem from the quality of model wind forcing that nowadays is generally adequate for the open ocean conditions (Winterfeldt and Weisse, 2009) but may severely underestimate wind speeds in semi-enclosed basins (e.g., Signell et al., 2005).

The shortages in forcing data and the scarcity of long-term instrumentally measured wave time series from the nBP make the available visually observed wave data sets an important source for the wave research in the Baltic Sea. The pattern of dominant winds (Soomere and Keevallik, 2001), the geometry of the Baltic Sea, and the existing wave climate hindcasts (Räämet and Soomere, 2010) suggest that the highest and longest waves usually occur either at the entrance of the GoF, at the eastern coast of the Baltic Proper (BP), along the Polish coasts, and in the Arkona basin. Historical visual wave data from the north-eastern (downwind) parts of the BP thus form an extremely valuable data set for identification of changes in the local wave climate.

Visual wave observations involve intrinsic quality and interpretation problems (Soomere and Zaitseva, 2007; Zaitseva-Pärnaste et al., 2009). They always contain an element of subjectivity, represent only wave properties in the nearshore and for a limited range of directions, usually have a poor spatial and temporal resolution and many gaps, may give a distorted impression of extreme wave conditions, etc. Their key advantage is the large temporal coverage. Regular visual observations started from the mid-1950s in many locations of the eastern coast of the Baltic Sea and have been carried out with the use of a unified procedure until today (Soomere and Zaitseva, 2007).

The basic features of wave fields and their long-term changes along the Estonian coasts such as the distributions of wave heights and periods and seasonal and interannual variations of the average wave properties have been analysed in detail in (Zaitseva-Pärnaste et al., 2009; Räämet and Soomere, 2010) based on comparisons of measured and observed data with the results of numerical hindcast.

In this study we mainly focus on the properties of the largest waves and their variations along the coasts of the north-eastern Baltic Sea. The analysis relies on comparison of joint two-dimensional (2D) distributions of visually observed and modelled wave properties (scatter diagrams) for historical wave data sets from the eastern part of the nBP (Vilsandi) and the GoF (Pakri, Narva-Jõesuu) and for results of modelling of wave properties over the last 38 years in this region. A relatively good match of these distributions allows for an adequate estimate of the combinations of wave heights and periods in the strongest storms over the entire time interval covered by the data. This match also suggests that numerically hindcast extreme wave conditions correspond well to the realistic roughest seas. Further on, we make an attempt to identify potential changes in the wave heights in strongest storms based on 99%-iles and 95%-iles of the modelled significant wave height for each calendar year. Finally, we take a short look at changes in the directional distributions of wave fields – a feature that may substantially affect the evolution of sedimentary coasts.

2. DATA AND THE MODEL

The analysis below is based on three visually observed wave data sets recorded at (i) the western coast of the island of Vilsandi (58°22′59″N, 21°48′55″E), (ii) Pakri in the western part of the GoF (59°23′37″N, 24°02′40″E), and (iii) Narva-Jõesuu in the eastern part of this gulf (59°28′06″N, 28°02′42″E) in Narva Bay (Fig. 1). Systematic wave observations at these sites started in 1954 and have been carried out until today (until 1985 at Pakri).

Fig. 1. Location scheme of the wave observation sites.

Data from Vilsandi reflect well waves coming from the westerly directions (Soomere and Zaitseva, 2007), but the largest waves may be distorted owing to a shallow water depth at the observation site. Pakri is the only deep-water wave observation site on the southern coast of the GoF that is largely open to waves generated in the nBP (Zaitseva-Pärnaste et al., 2009). Waves at Narva-Jõesuu are frequently locally generated and usually stem from the GoF. The site is fully open to waves approaching from the north-west and almost open to waves approaching from the south-west to the north. The height of the observation platform is 12.8 m above mean sea level. This allows even better wave observation conditions than at Vilsandi. The measurement routine was identical for all observation sites (Soomere and Zaitseva, 2007).

The properties of wave fields were hindcast with the use of the third generation spectral wave model WAM (Komen et al., 1994). The calculation was made for a regular rectangular grid (resolution about 3 × 3 nautical miles, 239 × 208 points, 11 545 sea points) based on the bathymetry prepared by Seifert et al. (2001) that extends over the ice-free sea from 09°36′E to 30°18′E and from 53°57′N to 65°51′N (Soomere, 2003). At each sea point, 1008 components of the 2D wave spectrum were calculated. The model uses 24 evenly spaced directions. Differently from the standard configuration of the WAM (which ignores waves with periods <2 s), an extended frequency range from 0.042 to about 2 Hz (wave periods 0.5–23.9 s, 42 frequencies with an increment of 1.1) was used to ensure realistic wave growth rates in low wind conditions after calm situations (Soomere, 2005).

The wind forcing at a 10 m level was derived from geostrophic winds as recommended by Bumke and Hasse (1989): the geostrophic wind speed was multiplied by 0.6 and the direction turned by 15° to the left. This approximation is used in many contemporary studies into the Baltic Sea dynamics (Myrberg et al., 2010). An analysis of the performance of the model is presented in (Räämet and Soomere, 2010). The results are called modelled or hindcast data below.

3. RESULTS

3.1. Wave properties in extreme storms

The combinations of wave heights and periods in the roughest storms can be best estimated from the empirical 2D distributions of the joint probability of the occurrence of wave conditions with different heights and periods (Fig. 2). Such distributions are sometimes also called scatter diagrams of wave heights and periods (Kahma et al., 2003). The most typical combinations of wave properties apparently correspond to the points that are located at the “crests” of this distribution, which is interpreted as a surface elevation map. An exact definition of these crests can be given in terms of differential geometry: the crests are the lines of the curvature corresponding to the minimum normal curvature of the surface and going through a maximum of the surface. In particular, the direction along a crest is normal to the direction of the steepest descent. If such lines can be constructed and extended towards extreme wave conditions, their location indicates the combinations of the expected properties of extreme wave storms.

For the Baltic Sea conditions such diagrams have a regular shape of an elongated hogback-like elevation that is slightly curved along the conditions corresponding to fully developed seas with the Pierson–Moskowitz (PM) spectrum (Fig. 2). Similar diagrams for the open sea conditions usually represent a superposition of two such elevations. One of them is equivalent to those in Fig. 2 and corresponds to windseas whereas the other represents swells with relatively large periods and moderate or low heights. The latter branch is almost degenerate in the Baltic Sea where it becomes evident as a pool of waves with periods of 8–12 s and heights below 0.5 m (Soomere, 2008: fig. 4). A specific feature of the Baltic Sea is that a large part of the wave conditions are represented by points lying considerably to the left of the curve reflecting the PM spectrum and corresponding to high and short, thus very steep waves. Such conditions are frequently connected with acute danger to ships (Toffoli et al., 2005).

The instrumental data from Almagrundet and Bogskär in the north-eastern part of the BP and from a directional

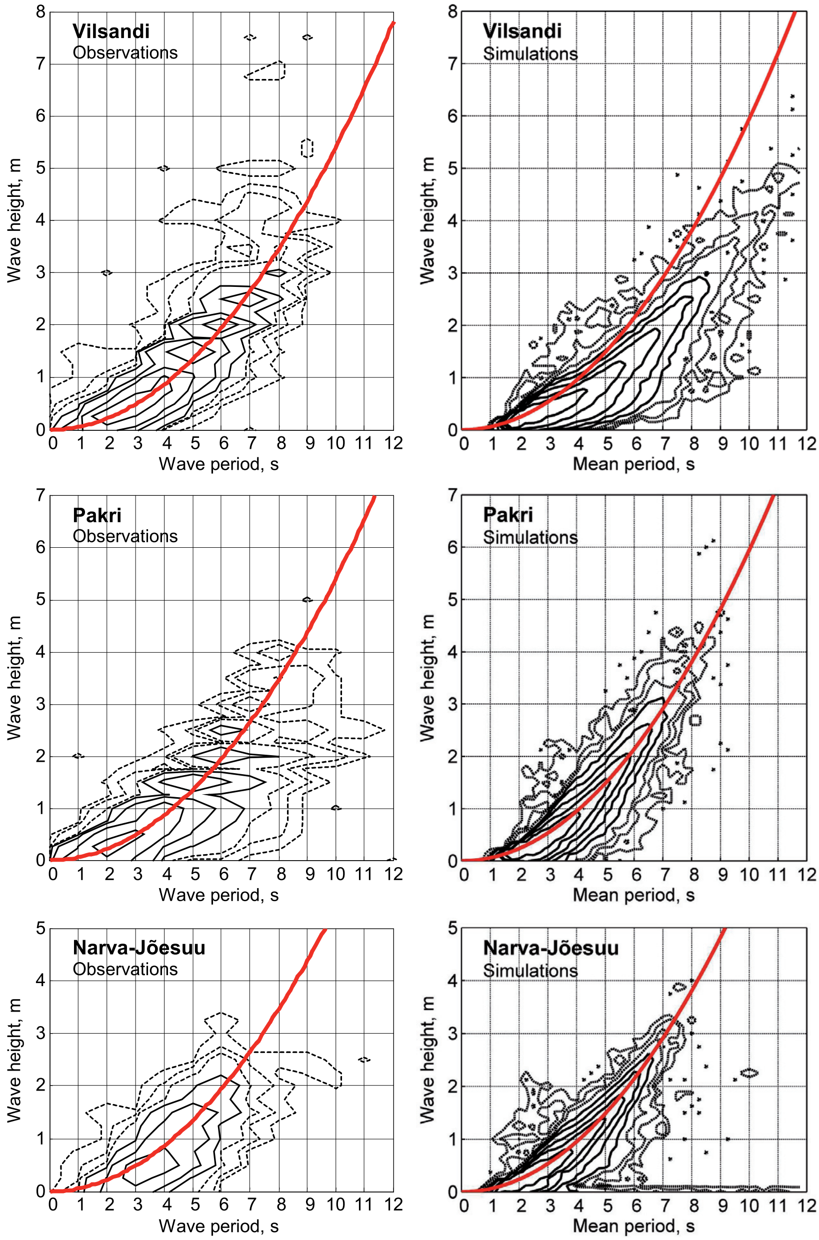

Fig. 2. Joint distribution of observed (all sensible wave observations with a non-zero wave period at Vilsandi (1954–1994), Pakri (1954–1985), and Narva-Jõesuu (1954–1974)) and modelled (1970–2007) wave heights and periods. The wave height step is 0.25 m for observed and 0.125 m for modelled data. Isolines for 1, 3, 10 (dashed lines), 33, 100, 330, 1000, and 3300 (solid lines) cases are plotted. The bold line shows the height of the fully developed waves with the PM spectrum for the given mean period.

waverider (Fig. 1) in the central part of the nBP (Kahma et al., 2003; Soomere, 2008) show that the roughest seas in the Baltic are generally steeper than the fully developed waves. The highest waves ($H_S \geq 7$ m) correspond to mean periods of 8–9 s at Almagrundet and to peak periods of 9–11 s at Bogskär and in the nBP (Soomere, 2008).

The scatter diagrams for observed and modelled waves are similar at all observation sites for low and moderate wave conditions up to wave heights of 3 m (Fig. 2). The properties of the most frequent low and moderate wave fields almost exactly match those of fully developed waves. While almost no swells have been recorded at Vilsandi, a larger proportion of relatively long waves for the given wave height is evident at Pakri and Narva-Jõesuu. This difference apparently reflects the more sheltered locations of these sites where swells may frequently dominate.

The distributions reflecting numerically simulated wave conditions are narrower. This feature probably reflects relatively large uncertainties in the visual detection of wave properties within a short time interval. Another source of differences is the finite resolution of the wave model: the observation site usually does not coincide with the nearest grid point for which the wave properties are calculated. The simulated distributions suggest that moderate and rough windseas are generally (i) clearly less steep than fully developed waves at Vilsandi, (ii) somewhat steeper at Pakri, and (iii) match the properties of wave fields with the PM spectrum at Narva-Jõesuu.

The largest difference in the shape of the distributions for observed and hindcast waves is found at Vilsandi. For example, the typical observed and modelled periods of 4 m high waves are about 8 and 10 s, respectively. A probable reason for this difference is the limited water depth (3–4 m) of the observation area at Vilsandi where waves higher than 3 m may already break and their heights may be easily overestimated. Thus, the hindcast distribution apparently provides a more adequate estimate for the wave properties in strong storms at Vilsandi.

The highest waves occurring once in about 40 years may reach 6.5 m in the deeper nearshore at Vilsandi and about 6 m at Pakri. Notice that observed wave heights of 7–8 m at Vilsandi are obviously overestimated because of quite a shallow depth at the observation area (Soomere and Zaitseva, 2007); yet wave heights >7 m have occurred about twice a decade in the northern Baltic Proper (Soomere, 2008). The corresponding mean wave periods were 11–12 s at Vilsandi, but much shorter, about 9–10 s, at Pakri. The difference in the periods apparently reflects the longer fetch for Vilsandi whereas the maximum wind speed in north-western storms (which create the largest waves at Pakri but have a shorter fetch) exceeds that for south-western storms (Soomere and Keevallik, 2001).

A similar difference in periods persists for somewhat smaller waves: about 5 m high waves have periods of about 11 s at Vilsandi but around 9 s at Pakri. The difference decreases for about 4 m high waves, which should have periods of 9–11 s and 7–9 s, respectively. At Narva-Jõesuu already 4 m high waves are extreme. Their period is expected to be about 7–8 s, that is, the same as at Pakri and by about 2 s shorter than at Vilsandi.

The 1D distributions of the frequency of occurrence of different wave heights and periods can be obtained from distributions in Fig. 2 by integration in the horizontal or in the vertical direction. They have been thoroughly discussed in earlier studies (Kahma et al., 2003; Broman et al., 2006; Soomere and Zaitseva, 2007; Soomere, 2008; Zaitseva-Pärnaste et al., 2009; Räämet and Soomere, 2010). The most frequent wave periods correspond to low waves of about 0.5 m and are 3–5 s in the open sea and 2–4 s in coastal areas. Larger waves have longer periods as indicated in Fig. 2. A somewhat unexpected feature is that the observed data set for Narva-Jõesuu contains a larger proportion of observed waves with periods 3–4 s compared to Pakri or Vilsandi. A probable reason for such a large content of longer waves is that frequent westerly winds may bring to Narva Bay appreciable quantities of remotely generated wave energy, optionally stemming already from the nBP.

The described overall match of the shape and basic properties of the analysed joint distributions of wave heights and periods suggests that the wave model in question properly reproduces the long-term statistics of wave fields in the north-eastern Baltic Sea. This conjecture motivates its use for the analysis of temporal variations of wave properties in severe storms.

3.2. Long-term variations of extreme wave heights

Recent analyses of visually observed data at three sites in question, instrumentally measured data at Almagrundet, and numerically simulated data revealed no clear trend in the annual mean wave heights (Soomere and Zaitseva, 2007; Räämet and Soomere, 2010). Instead, there is drastic interannual and decadal variability, with a typical time scale of 20–30 years, the increasing phase(s) of which have been at times interpreted as evidence of an increase in wave heights (Broman et al., 2006).

The above analysis suggests that visual observations provide no adequate data for estimates of long-term changes in extreme wave conditions. As the observed and simulated wave statistics match each other well, we discuss such variations based on the simulated values of the 99%-ile and 95%-ile of H_S for each calendar year.

The temporal course of both percentiles (Fig. 3) reveals quite large, mostly synchronous interannual and decadal variability in extreme wave conditions at all sites. There were relatively low extreme waves in 1976–

1980 and 1985–1988 whereas in 1989–1995 they were clearly higher. The correlation coefficients between the 95%-ile and the annual mean wave height are quite high, 0.9 at Vilsandi and Pakri and 0.84 at Narva-Jõesuu. The correlation of the 99%-ile with the 95%-ile varies from 0.76 to 0.79 and is somewhat smaller, about 0.7 with the annual mean wave height. The variations are also highly correlated at different sites: the relevant correlation coefficients are 0.75–0.88 for both percentiles.

A qualitative comparison of the discussed results for Vilsandi with similar data calculated with the use of a fetch-based model and one-point wind (Suursaar and Kullas, 2009; Zaitseva-Pärnaste et al., 2009) reveals that the short-term variability in the results of different models is qualitatively similar, but decadal variations are at times quite different and are almost not correlated for some decades. This feature apparently stems from the better ability of the WAM model and adjusted geostrophic wind fields to reproduce the extreme events.

The analysis in (Suursaar and Kullas, 2009; Zaitseva-Pärnaste et al., 2009) indicated a pronounced increase in the 99%-ile and a clear decrease in the mean wave height for the Vilsandi area over the recent past. Somewhat surprisingly, the modelled data show no statistically significant trend of any of the percentiles. There is, instead, a very small increase in the modelled values at Vilsandi (Fig. 3). A very slight increase is present in the 95%-ile and a similar slight decrease in the 99%-ile at Pakri and Narva-Jõesuu. Moreover, no statistically significant trend exists for any of the numerically simulated attributes of the wave fields under discussion.

3.3. Wave directions

The direction of visually observed wave propagation was interpreted as the direction from which the waves approach, similarly to the definition of the wind direction (Soomere and Zaitseva, 2007). The opposite interpretation in the WAM model is reversed below so that all the figures reflect the wave approach direction. The observations were recorded with the resolution of 45°. The ambiguity in the use of zero values at different sites and times (calm seas or waves propagating from the north) was resolved based on other measured parameters. A few doubtful cases are left out from the analysis. The main difference here compared with the analysis of the observed wave heights (Soomere and Zaitseva, 2007; Zaitseva-Pärnaste et al., 2009) is that all consistent observations of wave directions up to three times a day have been taken into account. A large number of wave conditions with zero wave heights and various wave directions from the eastern sector filed at Vilsandi apparently correspond to weak wave fields excited by winds blowing offshore from the measurement site. There are very few such cases at the other sites. The directional resolution of the WAM output in terms of the position of the spectral peak is 1° but the realistic resolution obviously cannot be considerably better than the directional resolution of the grid (15°), and the simulated wave propagation directions are divided into 32 sectors, each covering 11.25°.

The predominant wave directions match the directional structure of the prevailing winds and the geometry of the nearshore of the observation sites (Fig. 4). Vilsandi is fully open to winds and waves from the south-western, western, and north-western directions. The two-peak distribution of modelled waves follows the wind pattern in the nBP where strong winds blow from the south-west or north-west (Soomere and Keevallik, 2001). The observed distribution follows the same pattern but is to some extent smoothed due to the low directional resolution. Waves approach Pakri mostly from the west (although the site is also fully open to the north), and Narva-Jõesuu from the W–NW direction and again the modelled and observed directions generally match each other.

The simulated propagation distributions for all waves and for moderate and high waves ($H_S > 0.5$ m) almost coincide whereas the ones for the higher waves have slightly narrower and higher peaks. Thus, one of the most interesting properties of wind fields in the GoF (that the direction of the strongest winds does not match the direction of most frequent winds (Soomere and Keevallik, 2003)) is not represented in wave simulations.

The directional distributions of wave approach show a certain interannual and decadal variability for Vilsandi and Pakri but reveal no substantial long-term changes of the predominant direction. As expected from Fig. 4, this distribution has a specific two-peak structure at Vilsandi (Fig. 5) and one peak for an almost fixed direction at Pakri.

Substantial changes in the predominant wave direction have occurred in Narva Bay during the half-century of observations (Fig. 6). Waves mostly approached from the W–NW direction in the 1950s and until about 1965. The predominant approach direction moved almost to the north for the 1970s. Further on, it turned considerably, from the north-west to the south-west (for some years even almost to the south) over the 1980s. Then it switched between the W–SW and the south and has been mostly from the south within the latter decade. The most frequent observed propagation direction, therefore, has changed by more than 90° over the half-century of the observations. The second most frequent wave direction (S–SE) has turned in a similar manner but to a lesser extent. Interestingly, none of these changes are reflected in simulated wave propagation directions (Fig. 6).

The nature of the described changes obviously needs further research, which is out of the scope of this paper. The observed data on wave propagation do not reflect all wave conditions at Vilsandi where for certain years only wave height was recorded (Soomere and Zaitseva, 2007). At Narva and Pakri, wave direction is recorded more regularly (Fig. 7), but still the amount of sensible wave direction recordings is smaller than the number of recorded wave heights. Consequently, the reliability of the analysis of the number of wave conditions (that have been divided between different directions) is much lower than that for wave heights.

Another phenomenon potentially affecting the results in question is that the observer may tend to overestimate the role of relatively short waves whereas a long low swell frequently remains undetected as documented for the Tallinn Bay conditions (Orlenko et al., 1984). As the proportion of long waves is quite large at Narva, this feature of visual observations may lead to a certain overestimation of the frequency of locally generated wave fields.

There are still several arguments suggesting that the turn in question reflects certain changing features of the local wave fields. The change in the coverage of observations in the annual scale, albeit clearly visible from Fig. 7, concerns only the lengthening of the typical observation season by 1–2 months. As in these months only one observation per day was possible in daylight, the changing amount of observations evidently cannot affect so strongly the predominant wave direction. The turn in question evolves gradually over many years and evidently is not related to potential inhomogeneities stemming, for example, from the change of observers. It is highly unlikely that changes in the local wave generation conditions (for example, the diurnal breeze cycle) have led to the described phenomenon.

4. DISCUSSION AND CONCLUSIONS

Comparison of modelled and observed wave statistics confirms that the model satisfactorily represents the basic statistics of the north-eastern Baltic Sea wave fields and is an appropriate tool for studies of the combinations of wave heights and periods in strong storms and of long-term changes in properties of rough seas. The overwhelming domination of windseas suggests that the impact of remote swells is negligible.

Both visual wave observations and simulations with the WAM model and properly adjusted geostrophic winds suggest that there has been no clear trend in severe wave heights (in terms of simulated 95%-ile and 99%-ile) in the north-eastern Baltic Proper and in the western part of the GoF. Although this conclusion does not entirely match the results of several earlier studies, it reflects the limits of the reproduction of the Baltic Sea wave climate with the use of the geostrophic winds. These winds are generally believed to mirror the basic changes in the wind fields in the open ocean but may fail to do so in semi-enclosed basins surrounded by substantial topographic features. Therefore, it is not entirely surprising that the performed simulations failed to reproduce some wave properties in the Baltic Sea basin and that simulations based on more elaborated wind data are necessary to replicate certain aspects of wave climate in this water body.

The north-eastern coasts of the Baltic Proper develop under the impact of high waves that come alternatively from the south-west and the N–NW. The duration of wave events generated by south-westerly winds is clearly longer, but the impact of waves approaching from the N–NW may be almost as strong because winds from this direction may be stronger.

A highly interesting feature, however, is the substantial turn of the predominant observed wave propagation direction in Narva Bay. Even though the visual observations may contain errors and are strongly observer-dependent, the systematic rotation by more than 90° over half a century can be interpreted as an evidence of certain changes in the wind fields over the GoF, possibly connected with the overall increase in the role of south-western winds over Estonia (Kull, 2005).

This turn, however, does not necessarily bring about drastic consequences for the evolution of the sedimentary coasts nearby. For example, the evolution of beaches in Narva Bay is governed by the predominant largest waves that continue to approach from the west to the north even when the formal frequency of wave conditions from these directions has somewhat decreased. The increase in the frequency of waves from southerly directions obviously will cause no large changes in the coastal processes in Narva Bay as these waves are small and short and never occur in high water level conditions.

Further understanding of the spatial extent of the described phenomenon and its magnitude in terms of changes to the energy flux are highly important because it is not excluded that such changes reflect not yet identified properties of wind and wave fields in the eastern part of the Gulf of Finland that may have consequences in the coastal development in affected areas.

ACKNOWLEDGEMENTS

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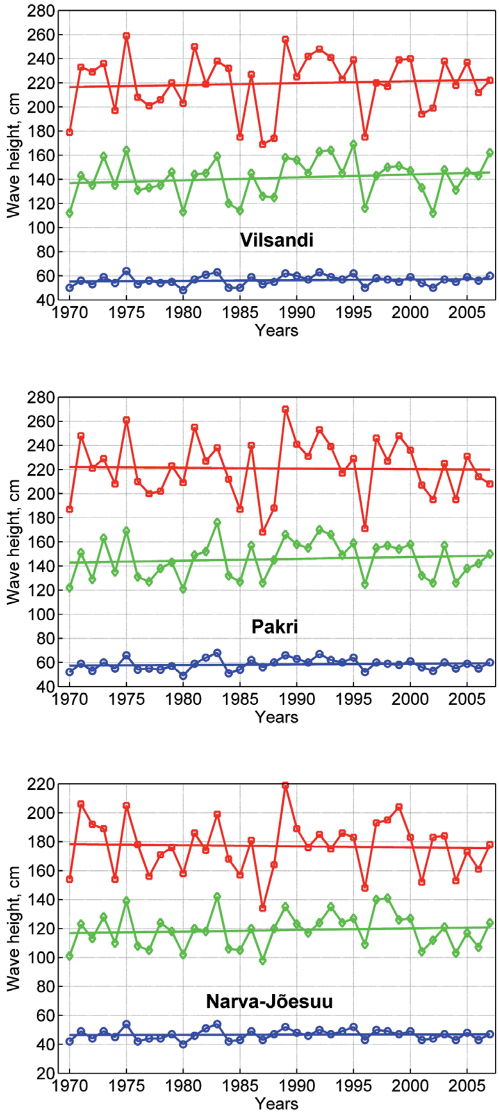

Fig. 3. The annual 99%-ile (red line) and 95%-ile (green line) values of wave heights and the annual mean wave height (blue line). The straight lines show the linear trends.

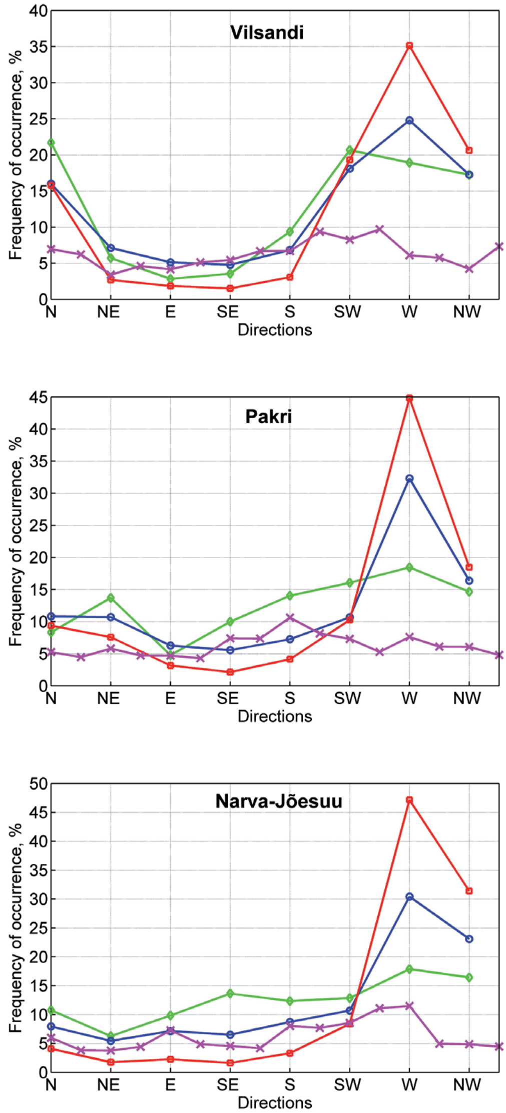

Fig. 4. Distribution of the wind directions (magenta; Kalbådagrund data are used for Narva-Jõesuu) and approach directions of observed (green, all sensible observations) and modelled waves (blue: all waves, red: waves >0.5 m).

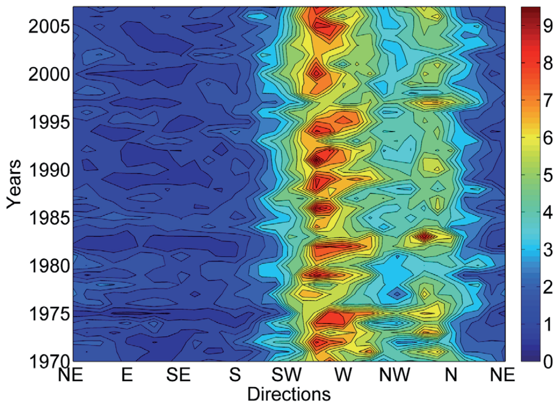

Fig. 5. Modelled directional distribution of wave approach for 1970–2007 at Vilsandi. Colour code shows the frequency of occurrence (%) of waves from a particular direction.

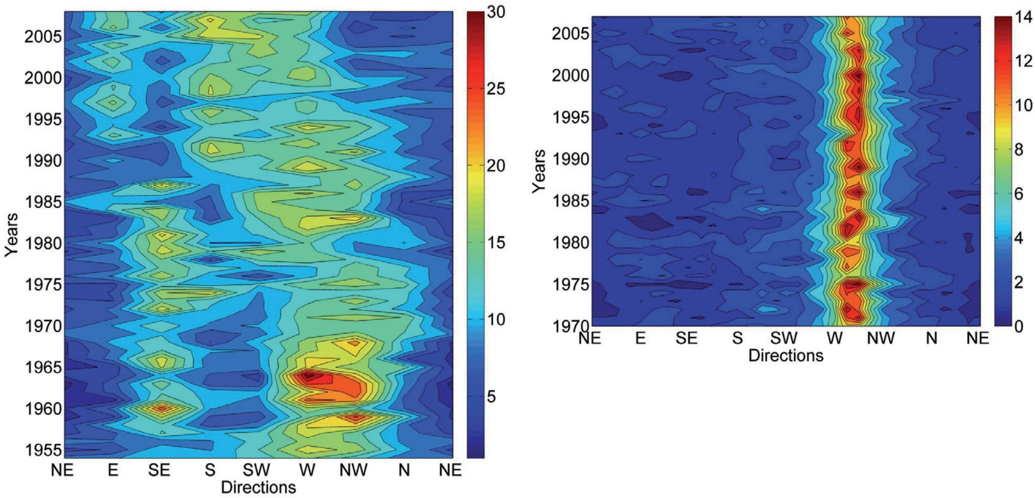

Fig. 6. Observed (left panel, 1954–2008) and modelled (right panel, 1970–2007) directional distribution of wave approach at Narva-Jõesuu. The colour code shows the frequency of occurrence (%) of waves from a particular direction.

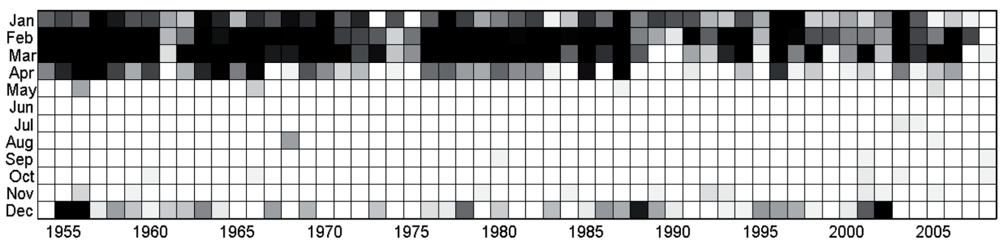

Fig. 7. The number of days with at least one sensible observation of wave directions at Narva-Jõesuu. White cells show 100% coverage, different shades of grey correspond to lower coverage with black indicating absence of observations for the relevant month.

Institute, especially to Dr Barry Broman, for providing geostrophic winds for the Baltic Sea basin, and to the Finnish Meteorological Institute for providing Kalbådagrund wind data. Comments and suggestions from two anonymous reviewers helped to considerably improve the interpretation of the results.

REFERENCES

Alexandersson, H., Schmith, T., Iden, K., and Tuomenvirta, H. 1998. Long-term variations of the storm climate over NW Europe. *Global Atmos. Ocean Syst.*, **6**, 97–120.

Alexandersson, H., Tuomenvirta, H., Schmith, T., and Iden, K. 2000. Trends of storms in NW Europe derived from an updated pressure data set. *Climate Res.*, **14**, 71–73.

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

Bacon, S. and Carter, D. J. T. 1993. A connection between mean wave height and atmospheric pressure gradient in the North Atlantic. *Int. J. Climatol.*, **13**, 423–436.

Broman, B., Hammarklint, T., Rannat, K., Soomere, T., and Valdmann, A. 2006. Trends and extremes of wave fields in the north-eastern part of the Baltic Proper. *Oceanologia*, **48**(S), 165–184.

Bumke, K. and Hasse, L. 1989. An analysis scheme for determination of true surface winds at sea from ship synoptic wind and pressure observations. *Boundary-Layer Meteorol.*, **47**, 295–308.

Grabemann, I. and Weisse, R. 2008. Climate change impact on extreme wave conditions in the North Sea: an ensemble study. *Ocean Dynamics*, **58**(3–4), 199–212.

Günther, H., Rosenthal, W., Stawarz, M., Carretero, J. C., Gomez, M., Lozano, I., Serano, O., and Reistad, M. 1998. The wave climate of the Northeast Atlantic over the period 1955–1994: the WASA wave hindcast. *Global Atmos. Ocean Syst.*, **6**, 121–163.

Helminen, J. 2006. Finnish local view on the factors accounting for the costs of weather-related disasters (specifically, floods and storms) in recent decades and implications of understanding these for both research and policy. In *Workshop on Climate Change and Disaster Losses: Understanding and Attributing Trends and Projections, 25–26 May 2006, Hohenkammer, Germany* (Höppe, P. and Pielke, R. Jr., eds), 134–144.

Jaagus, J., Post, P., and Tomingas, O. 2008. Changes in storminess on the western coast of Estonia in relation to large-scale atmospheric circulation. *Climate Res.*, **36**, 29–40.

Kahma, K., Pettersson, H., and Tuomi, L. 2003. Scatter diagram wave statistics from the northern Baltic Sea. *MERI – Rep. Ser. Finnish Inst. Mar. Res.*, **49**, 15–32.

Keevallik, S. and Soomere, T. 2004. Trends in wind speed over the Gulf of Finland 1961–2000. In *Fourth Study Conference on BALTEX, Scala Cinema, Gudhjem, Bornholm, Denmark, 24–28 May 2004* (Isemer, H.-J., ed.). International BALTEX Secretariat, Publication No. 29, 129–130.

Kelpšaite, L., Herrmann, H., and Soomere, T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proc. Estonian Acad. Sci.*, **57**, 225–231.

Kelpšaite, L., Parnell, K. E., and Soomere, T. 2009. Energy pollution: the relative influence of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea. *J. Coastal Res.*, Special Issue, **56**, Vol. I, 812–816.

Komen, G. J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., and Janssen, P. A. E. M. 1994. *Dynamics and Modelling of Ocean Waves*. Cambridge University Press, Cambridge.

Kull, A. 2005. Relationship between interannual variation of wind direction and wind speed. *Publ. Inst. Geogr. Univ. Tartu.*, **97**, 62–73.

Kushnir, Y., Cardone, V. J., Greenwood, J. G., and Cane, M. A. 1997. The recent increase in North Atlantic wave heights. *J. Climate*, **10**, 2107–2113.

Myrberg, K., Ryabchenko, V., Isaev, A., Vankevich, R., Andrejev, O., Bendtsen, J., Erichsen, A., Funkquist, L., Inkala, A., Neelov, I., Rasmus, K., Rodriguez Medina, M., Raudsepp, U., Passenko, J., Söderkvist, J., Sokolov, A., Kuosa, H., Anderson, T. R., Lehmann, A., and Skogen, M. D. 2010. Validation of three-dimensional hydrodynamic models in the Gulf of Finland based on a statistical analysis of a six-model ensemble. *Boreal Env. Res.*, **15**.

Orlenko, L. R., Lopatukhin, L. I., and Portnova, G. L. (eds). 1984. *Studies of the Hydrometeorological Regime of Tallinn Bay*. Gidrometeoizdat, Leningrad (in Russian).

Orviku, K., Jaagus, J., Kont, A., Ratas, U., and Rivis, R. 2003. Increasing activity of coastal processes associated with climate change in Estonia, *J. Coastal Res.*, **19**(2), 364–375.

Pryor, S. C. and Barthelmie, R. J. 2003. Long-term trends in near-surface flow over the Baltic. *Int. J. Climatol.*, **23**, 271–289.

Räämet, A. and Soomere, T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian J. Earth Sci.*, **59**, 100–113.

Räämet, A., Suursaar, Ü., Kullas, T., and Soomere, T. 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *J. Coast. Res.*, Special Issue, **56**, Vol. I, 257–261.

Seifert, T., Tauber, F., and Kayser, B. 2001. A high resolution spherical grid topography of the Baltic Sea. In *Baltic Sea Science Congress, Stockholm 25–29 November 2001*, Vol. 2, Poster # 147, www.io-warnemuende.de/iowtopo

Signell, R. P., Carniel, S., Cavaleri, L., Chiggiato, J., Doyle, J. D., Pullen, J., and Sclavo, M. 2005. Assessment of wind quality for oceanographic modelling in semi-enclosed basins. *J. Marine Syst.*, **53**(1–4), 217–233.

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

Soomere, T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Env. Res.*, **10**, 103–118.

Soomere, T. 2008. Extremes and decadal variations of the northern Baltic Sea wave conditions. In *Extreme Ocean Waves* (Pelinovsky, E. and Kharif, Ch., eds). Springer, 139–157.

Soomere, T. and Healy, T. 2008. Escalating extremes over descending trends of the northern Baltic Sea wave fields. In *Solutions to Coastal Disasters 2008* (Wallendorf, L., Ewing, L., Jones, C., and Jaffe, B., eds). American Society of Civil Engineers, 129–138.

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

Soomere, T. and Keevallik, S. 2003. Directional and extreme wind properties in the Gulf of Finland. *Proc. Estonian Acad. Sci. Eng.*, **9**, 73–90.

Soomere, T. and Zaitseva, I. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proc. Estonian Acad. Sci. Eng.*, **13**, 48–64.

Soomere, T., Behrens, A., Tuomi, L., and Nielsen, J. W. 2008. Wave conditions in the Baltic Proper and in the Gulf of Finland during windstorm Gudrun. *Nat. Hazards Earth Syst. Sci.*, **8**, 37–46.

Suursaar, Ü. and Kullas, T. 2009. Decadal variations in wave heights off Cape Kelba, Saaremaa Island, and their relationships with changes in wind climate. *Oceanologia*, **51**(1), 39–61.

Toffoli, A., Lefevre, J. M., Bitner-Gregersen, E., and Monbaliu, J. 2005. Towards the identification of warning criteria: analysis of a ship accident database. *Appl. Ocean Res.*, **27**(6), 281–291.

Zaitseva-Pärnaste, I., Suursaar, Ü., Kullas, T., Lapimaa, S., and Soomere, T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. *J. Coastal Res.*, Special Issue, **56**, Vol. I, 277–281.

Wang, X. L. and Swail, V. R. 2002. Trends of Atlantic wave extremes as simulated in a 40-yr wave hindcast using kinematically reanalyzed wind fields. *J. Climate*, **15**, 1020–1035.

WASA Group. 1998. Changing waves and storms in the northeast Atlantic? *Bull. Amer. Meteor. Soc.*, **79**, 741–760.

Weisse, R. and Günther, H. 2007. Wave climate and long-term changes for the southern North Sea obtained from a high-resolution hindcast 1958–2002. *Ocean Dynamics*, **57**(3), 161–172.

Winterfeldt, J. and Weisse, R. 2009. Assessment of value added for surface marine wind speed obtained from two regional climate models. *Mon. Weather Rev.*, **137**(9), 2955–2965.

Ekstreemsete lainetuse tingimuste ja lainete levikusuuna muutustest Eesti rannavetes

Andrus Räämet, Tarmo Soomere ja Inga Zaitseva-Pärnaste

Vilsandil, Pakril ja Narva-Jõesuus tehtud lainevaatluste ning kogu Läänemere lainete numbrilise modelleerimise baasil on hinnatud lainete kõrguste ja perioodide kombinatsioone ekstreemsetes tormides Läänemere kirdeosas ning Soome lahe lõunarannikul, kõrgeimate lainete omaduste muutusi aastail 1970–2007 ja lainete levikusuundade nurkjaotuse muutusi aastail 1954–2009. Ekstreemsetes tormides vastavad ligikaudu 7-meetrisele lainekõrgusele Läänemere avaosas lainete perioodid 10–12 s, 6-meetrisele lainekõrgusele Soome lahe suudmes perioodid 8–11 s ja 4-meetrisele lainekõrgusele perioodid 6–8 s lahe idaosas. On demonstreeritud, et modelleeritud lainekõrguste 95% ja 99% protsentiilid püsisid vaadeldaval ajavahemikul stabiilsetena. On näidatud, et lainete valdav saabumise suund on Narva-Jõesuus alates 1980. aastast muutunud ligikaudu 90° võrra loodest edelasse. Need muutused ei kajastu modelleeritud lainetuse omadustes.

Paper IV

Soomere T., **Zaitseva-Pärnaste I**., Räämet A. 2011. Variations in wave conditions in Estonian coastal waters from weekly to decadal scales. *Boreal Environment Research*, 16 (Suppl A), 175–190.

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Variations in wave conditions in Estonian coastal waters from weekly to decadal scales

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Historical visual observations and numerical hindcasts with the use of the WAM wave model and adjusted geostrophic winds are merged to reveal the basic features of the wave properties and to identify the variations in wave height in different scales in the coastal waters of Estonia. The visually observed wave properties from Vilsandi (1954–2008), Pakri (1954–1985) and Narva-Jõesuu (1954–2008) are compared against wave data hindcast for the entire Baltic Sea for 1970–2007. It is shown that the wave height follows the seasonal variation in wind speed with a maximum in October–January and with a substantial variability on weekly scales. The annual mean wave heights reveal nearly synchronous interannual variations along the entire coast of Estonia until the mid-1980s after which this coherence is lost. The length of the ice season is almost uncorrelated with the annual mean wave heights.

Introduction

The combination of significant wind anisotropy in the Baltic Sea basin, seasonal variation in the wind speed and complicated patterns of long-term changes in wind properties over the entire Scandinavian area (Pryor and Barthelmie 2003, 2010) gives rise to remarkable anisotropy and substantial large spatio-temporal variations in the Baltic Sea wave fields (Jönsson *et al*. 2002, Soomere 2003, Broman *et al*. 2006, Kelpšaitė *et al*. 2008). The information about the wave climate in this area, however, mostly relies on a few measurement sites and on short-term simulations of wave properties with a few years' duration (Soomere 2008). The information is particularly fragmentary for the eastern part of the Baltic Proper. Extremely complex geometry and large variations in wave propagation conditions characterise especially Estonian coastal waters and the Gulf of Finland (Soomere 2005, Laanearu *et al*. 2007, Soomere *et al*. 2008). While a limited amount of wave statistics from the 1990s is available from the central part of the Gulf of Finland for the ice-free time (Pettersson 2001), contemporary instrumental wave measurements are almost missing for the Estonian coastal area. Only recently, data covering five months of wave fields in the nearshore of Saaremaa (Suursaar and Kullas 2009) and one year near the NE coast of Estonia (Suursaar 2010) became available.

The existing data for the coastal areas of the northern Baltic Proper (nBP) reveal several highly interesting features of long-term behaviour of wave properties in this area. A rapid increase in the annual mean wave height in the nBP from the mid-1980s until the mid-1990s and an equally rapid decrease since then were established from both instrumental measurements (Broman *et al*. 2006) and visual observations (Soomere and Zaitseva 2007). While the increase in wave height generally matches similar trends in the North Sea, both the magnitude of the increase and the subsequent decrease in the nBP are somewhat counter-intuitive. Moreover, simple wave models based on one-point wind data did not reproduce these variations (Suursaar and Kullas 2009, Räämet *et al*. 2009). As the recorded changes occurred simultaneously and with a similar relative magnitude at both the eastern and western coasts of the nBP, it is still likely that they expose certain large-scale decadal variations in the wave properties in particular sea areas rather than failures of instruments or the relay of the observers.

An accurate picture of wave properties and their potential changes is necessary for a wide variety of research topics and coastal engineering applications. This problem is particularly important for the Baltic Sea where the impact of waves depends not only on the properties of wave fields but also on external features such as water level or the presence of ice cover. For example, changes in wave climate even in terms of shifts of the stormy season to months with no ice cover may lead to severe destruction of vulnerable beaches of the eastern Baltic Sea (Orviku *et al*. 2003, Ryabchuk *et al*. 2011).

Coarse wave measurements at a few sites along a highly variable coastline frequently do not contain sufficient information about spatial variability of wave fields, particularly in sea areas with complex geometry and nontrivial wind regime such as the Baltic Sea. While the use of visual wave observations has always been problematic because of the lack of reliable data from the open sea areas, nowadays various methods of wave modelling are most widely spread. Although there have been several successful attempts to reproduce local wave properties in the nearshore of Estonia based on one-point wind information and simplified wave models (Soomere 2005, Räämet *et al*. 2009, Suursaar 2010, Suursaar *et al*. 2010), the complexity of geometry and bathymetry of the Baltic Sea combined with extensive variations in the wind properties over the Baltic Sea leads to an acute need for the use of contemporary wave models and realistic wind fields in order to obtain reliable wave statistics. Räämet and Soomere (2010) have demonstrated that the wind wave climatology can be adequately estimated for the Baltic Proper and for the open sea of the Gulf of Finland based on properly adjusted geostrophic wind fields.

In this paper, we make an attempt to merge historical visual observations and numerical hindcasts to reveal seasonal, annual and decadal changes in the basic wave properties in different parts of Estonian coastal waters. As contemporary wave measurements are relatively scarce and short here, we combine different data sources with extensive modelling resources. We first describe the wave model in use and the pool of existing long-term wave observations and instrumental measurements in this area. The basic properties of wave fields such as distributions of the frequency of occurrence of waves of different height and period and short-term (weekly and seasonal) variations in the wave heights are discussed next. Further, long-term variations in the annual mean wave activity are analysed in terms of the mean significant wave height for both original and climatologically corrected data sets, and for 12-month-long time periods containing entire windy autumn and winter seasons.

Methods and data

The analysis below is largely based on visual wave observations at sites operated by the Estonian Meteorological and Hydrological Institute at Vilsandi (1954–2008, Soomere and Zaitseva, 2007), Pakri (1954–1985, Zaitseva-Pärnaste *et al*. 2009) and Narva-Jõesuu (1954–2008, Table 1 and Fig. 1). Features extracted from this data set are compared against instrumental measurements at Almagrundet (1978–2003) on the western coast of the Baltic Proper (Broman *et al*. 2006) and against numerically modelled wave data using the WAM model.

The wave observation routine and technology were identical at all visual observation sites.

As an overview of the routine of observations and a description of the data sets for the sites at Vilsandi and Pakri are given in (Soomere and Zaitseva 2007, Zaitseva-Pärnaste *et al*. 2009), we just present the key features of the routine here. Observations were only made in daylight. The initial observation times (07:00, 13:00 and 19:00 Moscow time, or GMT +3 hours) were shifted to 06:00, 12:00 and 18:00 GMT in 1991. This shift apparently did not cause any substantial inhomogeneity of the time series of the daily mean wave height, which is the property mostly used below.

The observational procedure resembles the classical zero-crossing method. The observer noted the five highest waves during a 5-minute time interval with an accuracy of 0.25 m for wave heights ≤ 1.5 m, 0.5 m for wave heights from 1.5 to 4 m, and 1 m for higher than 4 m waves. Both the height of the highest single wave H_{max} (called maximum wave height below) and the mean height H of these five waves were filed until about 1990. Given the typical wave period of about 2–4 s (*see* below), the estimated mean wave height was actually the average height of top 3%–6% of the waves and thus quite close to the maximum wave height. For the part of data where both the mean and maximum wave heights were filed, the maximum wave height was, on average, only by 6% higher than the mean wave height at Vilsandi (Soomere and

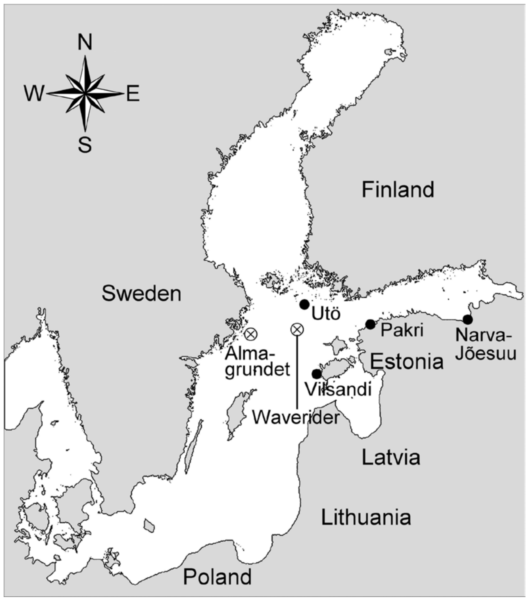

Fig. 1. Location scheme of the long-term wave measurement and observation sites in the Baltic Sea.

Table 1. Basic parameters of wave observations and properties at Vilsandi, Pakri and Narva-Jõesuu. Notice that part of the difference between the average values of the maximum and mean wave heights is connected with the availability of these parameters for different time intervals.

	Vilsandi 1954–2008	Pakri 1954–1985	Narva-Jõesuu 1954–2008
Co-ordinates	58°22´59´´N, 21°48´55´´E	59°23´37´´N, 24°02´40´´E	59°28´06´´N, 28°02´32´´E
Nearest grid point of the wave model WAM	58°24´N, 21°48´E	59°24´N, 24°00´E	59°30´N, 28°00´E
Consistent wave height entries			
total	27131	13283	35027
days covered	15977	9554	15863
Consistent wave period entries			
total	28016	10354	8488
days covered	12553	7724	3514
Largest maximum/mean wave height (m)	8/7.6	6/6	3.4/3.3
Average of the maximum wave heights (m)			
total mean	0.584	0.616	0.455
mean of daily values	0.621	0.610	0.462
Average of the mean wave heights (m)			
total mean	0.511	0.591	0.393
mean of daily values	0.539	0.589	0.391
Mean wave height based on mean of daily values	0.575	0.590	0.391
Number of calm conditions	11417	1923	4692

Zaitseva 2007). In the analysis below, the mean wave height is used; when it was missing, the maximum wave height was used instead. As the potential difference between these quantities is much smaller than the accuracy of the determination of the wave height, doing so did not insignificantly affect the wave statistics.

The wave period (length) was determined as an arithmetic mean from three consecutive observations of the passing time (total length) of 10 waves each time. These waves were not necessarily the highest ones. The experience with visual observations suggests that the observed wave height represents well the significant wave height (historically defined as the mean height of one third of the highest waves) whereas the estimated wave period is only a few tenths of seconds shorter than the peak period (Gulev and Hasse 1998, 1999).

A coastal site reasonably reflecting the nearshore sea state for the predominant strong wind directions (SW and NNW, Soomere and Keevallik 2001) in the nBP is at the Island of Vilsandi (Fig. 1). This site gives inadequate data for easterly winds, which are relatively weak and infrequent in this area. The observed wave properties reasonably well represent also the nearshore sea state conditions at Pakri in the western part of the Gulf of Finland (Fig. 1). Pakri is the only wave observation site on the southern coast of this gulf that is largely open to waves generated in the nBP (Zaitseva-Pärnaste *et al.* 2009). The average depth of the area at Pakri over which the waves were observed was 8–11 m. Unfortunately, wave observations were only performed at Pakri in 1954–1985.

The Narva-Jõesuu meteorological station (59°28´06´´N, 28°02´42´´E, Fig. 1) located on the coast of Narva Bay provides information about wave conditions in the eastern part of the Gulf of Finland. The site from which sea observations were made is located to the west of the station (Table 1). The height of the observation platform (12.8 m above the mean sea level) allows very good observation conditions over the wave observation area located about 200–250 m from the coast where the water depth is 3–4 m. As waves in the Gulf of Finland are generally much lower than in the Baltic Proper, waves do not break in the observation area under most wave conditions. The site is fully open to waves propagating from the NW direction and almost open to waves approaching from the west to the north. Data from Pakri and Narva were considered recently by Zaitseva-Pärnaste *et al.* (2009) as a reference data set allowing some verification of the changes to the wave climate in the Baltic Proper and by Räämet *et al.* (2010) from the viewpoint of potential changes to the wave propagation directions.

For certain comparisons, we use data from Almagrundet (1978–2003, 59°09´N, 19°08´E, Fig. 1; Broman *et al.* 2006), for which the longest instrumentally measured wave data sets in this region are available. Almagrundet is a shoal about 10 nautical miles SE of Sandhamn in the Stockholm archipelago. The fetch for winds from the SW, west, and NW is quite limited at this site. The position of the water surface was sampled over 640 s each hour with upward-looking echo-sounders. Single waves were identified using the zero-downcrossing method. An estimate of the significant wave height H_S was found from the 10th highest waves in a record under the assumption that wave heights are Rayleigh distributed. The water at the location of the instruments was deep enough (about 30 m) for most of the wave fields to follow the Rayleigh distribution of wave heights. The data from 1978–1995 reliably describes the wave properties in this region. Another data set from 1993–2003 have certain quality problems: the overall behaviour of the wave height is adequate but the periods are not usable (Broman *et al.* 2006).

All the listed sites are coastal and thus only conditionally represent open sea conditions. The sites are fully open to a range of predominant wind directions. The waves in the Baltic Sea are relatively short and thus less affected by the finite-depth effects compared to much longer ocean waves at a similar depth. The sheltering effect of the shoreline and the relatively low water depth at the observation sites still may at times significantly alter local wave properties compared to those in the open sea due to the shoaling, refraction and damping of the waves.

The most representative wave data for the nBP stem from a directional waverider operated by the Finnish Institute of Marine Research (FIMR) (from 2008 by the Finnish Meteorological Institute) in the nBP at a depth of about 100 m (Fig. 1, 59°15´N, 21°00´E) since September 1996 during the ice-free seasons (Kahma *et al*. 2003). Although this time series is not long enough for determining long-term variations in wave properties, we use this data as a reference set for comparisons with wave statistics at different sites.

The properties of wave fields at all three visual observation sites were also hindcast for the years 1970–2007 with the use of the third-generation spectral wave model WAM (Komen *et al*. 1994). The basic model setup follows the one described in (Soomere 2003). The presence of ice was ignored. The calculation was done for a regular rectangular grid with a resolution of about 3 × 3 nautical miles (11545 sea points) covering the entire Baltic Sea. At each sea point, 1008 components of the two-dimensional wave spectrum (24 evenly spaced directions, 42 frequencies starting from 0.042 Hz with an increment of 1.1) were computed. Differently from the standard configuration of the WAM model (that does not account for waves with periods < 2 s), an extended frequency range up to about 2 Hz (wave periods down to 0.5 s) was used to ensure realistic wave growth rates in low wind conditions after calm situations (Soomere 2005).

The WAM model was forced with a wind field derived from geostrophic winds provided by the Swedish Meteorological and Hydrological Institute (SMHI). In order to construct the near-surface wind at 10 m level, used as the input wind to the model, the geostrophic wind speed was multiplied by 0.6 and the direction turned by 15° to the left (cf. Bumke and Hasse 1989) as in many contemporary studies into the Baltic Sea dynamics (Myrberg *et al*. 2010). The wind time step was 6 hours before September 1977 and 3 hours since then.

Owing to the finite resolution of the wave model, there is always a certain difference between the location of an observation or measurement site and the nearest grid point for which the wave properties are calculated. The performance of the model, the match of the basic statistics of numerically simulated wave conditions with those observed at different sites and shortages connected with the use of different wind forcing are discussed in (Räämet and Soomere 2010). Several examples of the comparison of the time series and wave statistics of measured and observed data with the results of numerical simulations based on the WAM model and a simpler fetch-based model are provided by Räämet *et al*. (2009). The model performance was somewhat better for the Almagrundet area when the MESAN wind data (Häggmark *et al*. 2000) were used but for the open Baltic Sea the use of geostrophic winds showed a better match with the measurements.

The analysis below involves wave heights specified in three different manners: visually observed wave heights, the significant wave height calculated by using Rayleigh statistics at Almagrundet and the significant wave height estimated from the two-dimensional energy spectrum in the WAM model. The potential differences between these quantities, for example, because of a violation of the Rayleigh distribution in the nearshore, suggest that the instantaneous values and the average characteristics found from different sources may differ to some extent. On the other hand, the use of a particular method for obtaining an estimate for the wave height apparently does not distort the basic features of spatio-temporal variations in the wave fields such as their typical time scales and the direction and relative magnitudes of the trends.

Basic properties and seasonal variations of wave fields

The digitized data sets were first checked for consistency (e.g. whether large wave heights were associated with relative large periods). Joint distributions of wave heights and periods for the three observation sites are discussed by Räämet *et al*. (2010). A few (about 50) recorded wave heights > 4 m were interpreted as erroneous at Vilsandi where the water depth in the observation area is about 4 m (Soomere and Zaitseva 2007). Much higher waves, however, may occur at Pakri where the data set contains six cases when a maximum wave height was ≥ 5 m. These cases evidently correspond to realistic wave conditions in rough seas. The highest waves (6 m) were recorded on 6–7 August 1967 when a strong NW storm caused extensive

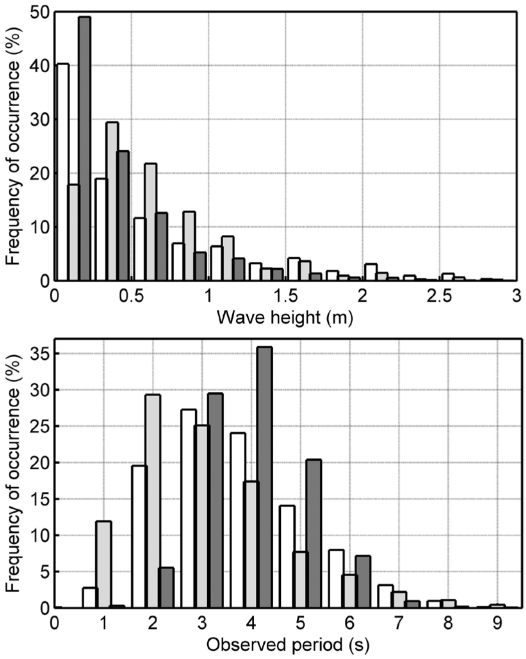

Fig. 2. Frequency of occurrence of different wave heights (above, resolution 0.25 m) and mean periods (below, resolution 1 s) at Vilsandi (white bars), Pakri (light grey bars) and Narva-Jõesuu (dark grey bars).

damage to the forests in Estonia. Waves with a height of 5 m were recorded on 21 January 1964 and on 23 September 1969.

As expected, the maximum wave heights were much lower at Narva-Jõesuu where they exceeded 3 m only four times. The largest maximum/mean wave heights (3.4/3.3 m) were recorded on 25 October 1957 and twice on 28 August 1961. Also on 15 October 1954 the maximum wave height over 3 m (maximum/mean 3.1/2.9 m) was observed.

The distributions of the occurrence of different wave heights at Vilsandi, Pakri and Narva-Jõesuu (Fig. 2) reflect all consistent observations of wave heights with non-zero wave periods. As there were systematically more observations per day in fairly calm spring and summer seasons, these distributions slightly overestimate the proportion of relatively low wave conditions. The distributions of wave periods are similarly biased. Notice that they reflect older observations as the periods were only recorded until the mid-1990s (Soomere and Zaitseva 2007: table 1).

The distributions in question reveal very high frequency of low waves with heights below 0.25 m at Vilsandi and Narva-Jõesuu (Fig. 2) and resemble analogous distributions for semi-sheltered bays of the Gulf of Finland (Soomere 2005). They are largely different from the analogous distributions for Almagrundet (Broman *et al*. 2006), for the nBP (Soomere 2008) and even for Pakri. Differently from Vilsandi and Narva-Jõesuu, the relevant distributions at Pakri, nBP and Almagrundet match the Rayleigh distribution well.

Although the Pakri observation site is sheltered from a part of the predominant SW winds, the distribution of wave periods at this site matches the distribution for the nBP (Kahma *et al*. 2003). The most frequent wave periods are 2–3 s. Interestingly, wave periods observed at Narva-Jõesuu are somewhat longer than those at Vilsandi and Pakri: the most frequent periods are 3–5 s as in the open part of the nBP (Kahma *et al*. 2003). This feature may be explained by a specific feature of wave generation and propagation in the Gulf of Finland. Namely, relatively long waves travelling along the axis of the gulf are frequently excited in this water body even when the wind blows obliquely with respect to this axis (so-called slanted fetch conditions, Pettersson 2004, Pettersson *et al*. 2010).

In order to remove the bias caused by the larger number of observations per day during the relatively calm spring and summer seasons, the entire analysis below is based on the set of daily mean wave heights (Soomere and Zaitseva 2007, Zaitseva-Pärnaste *et al*. 2009). The average wave height, calculated from daily mean wave heights, is 0.511 m at Vilsandi, 0.591 m at Pakri, and 0.393 m at Narva-Jõesuu (Table 1). This is clearly smaller than the mean significant wave height at Almagrundet (0.876 m in 1978–1995 and 1.04 m in 1993–2003, Broman *et al*. 2006). The wave height medians are 0.3 m, 0.5 m and 0.35 m for Vilsandi, Pakri and Narva-Jõesuu, respectively; these are also much smaller than at Almagrundet. Notice that the presented mean values in some cases reflect different time intervals and thus are not always directly comparable.

In general, all the data sets, albeit to some extent affected by the presence of the coast, reproduce the basic features of the northern Baltic Sea wave fields (Soomere 2008) such as

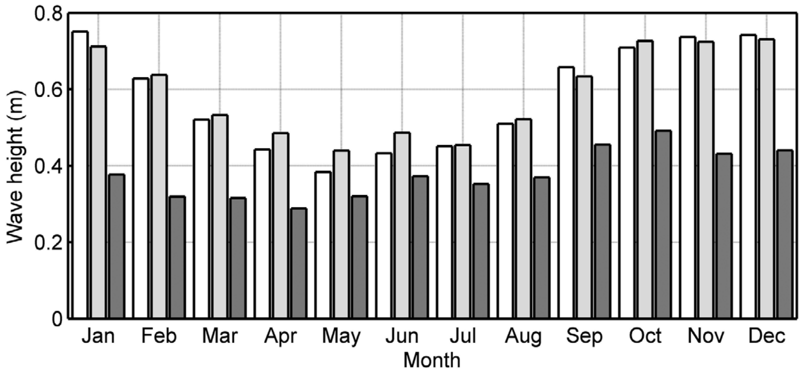

Fig. 3. Seasonal variation in the monthly mean wave height at Vilsandi (white), Pakri (grey) and Narva-Jõesuu (dark grey).

(i) the overall mild wave regime in the basin, with the overall mean wave height in the open sea approximately 1 m, in the coastal areas 0.5–0.6 m (Suursaar and Kullas 2009) and in semi-sheltered bays about 0.3–0.4 m (Soomere 2005); (ii) a large proportion of wave conditions with the significant wave heights around 0.5 m (Fig. 2), and (iii) the most frequent peak periods 4–6 s in the open sea and 2–4 s in the nearshore regions (Fig. 2). The listed values are characteristic of relatively small basins and are considerably smaller than the respective values for the open ocean.

The seasonal course of the wave heights at the observation sites is discussed by Räämet and Soomere (2010) and we present here only its main features. The wave conditions exhibit a strong seasonal variability at all sites (Fig. 3), which is the most pronounced at Vilsandi where the monthly mean wave height varies from about 0.38 m during summer to about 0.75 m in winter. The highest wave activity occurs in January and almost as high waves are observed from October to December. The calmest months are the spring and summer months from March to August, with a well-defined minimum in April or May. Such an annual variation mostly matches the annual variation of the wind speed in the nBP (Mietus 1998, Räämet and Soomere 2010). It also resembles the cycle of water level in adjacent coastal waters of Finland (Johansson *et al*. 2001).

The seasonal variation in the wave heights is much more pronounced at Almagrundet where the mean wave heights in the roughest and in the calmest months differ 2.2–2.6 times (Broman *et al*. 2006). This difference most probably stems from the impact of the coast upon visually observed wave conditions (Soomere and Zaitseva 2007). Almagrundet is located far enough from the coast to capture to some extent the properties of waves created by winds blowing offshore from the mainland while at the coastal sites the observer usually files calm seas under such conditions (cf. Table 1).

Although Pakri is sheltered from some of the waves excited by the most frequent (SW) winds, the overall mean wave height at Pakri and its seasonal variation almost exactly coincide with those at Vilsandi. Interestingly, the long-term observed and simulated wave heights also almost exactly coincide at this site (Räämet and Soomere 2010). This feature suggests that Pakri wave data to a large extent capture the wave conditions in the open sea but also indicates that the simulations in (Räämet and Soomere 2010) apparently underestimate the wave heights in the open sea.

There is a less pronounced but still clearly identifiable annual cycle in wave activity at Narva-Jõesuu (Fig. 3). The calmest months at this site are, as mentioned above, April and May. Differently from other sites, the roughest months in Narva Bay are September and October, when the monthly mean wave height exceeds 0.4 m. Relatively low values of the monthly mean wave heights at this site in November–December compared with those in October apparently reflect the frequent presence of sea ice on the coasts of Narva Bay and in the entire eastern Gulf of Finland in late autumn (Sooäär and Jaagus 2007).

There are some interesting variations in wave intensity within certain months. They become evident through the analysis of the climatological mean wave heights for single days (Fig. 4).

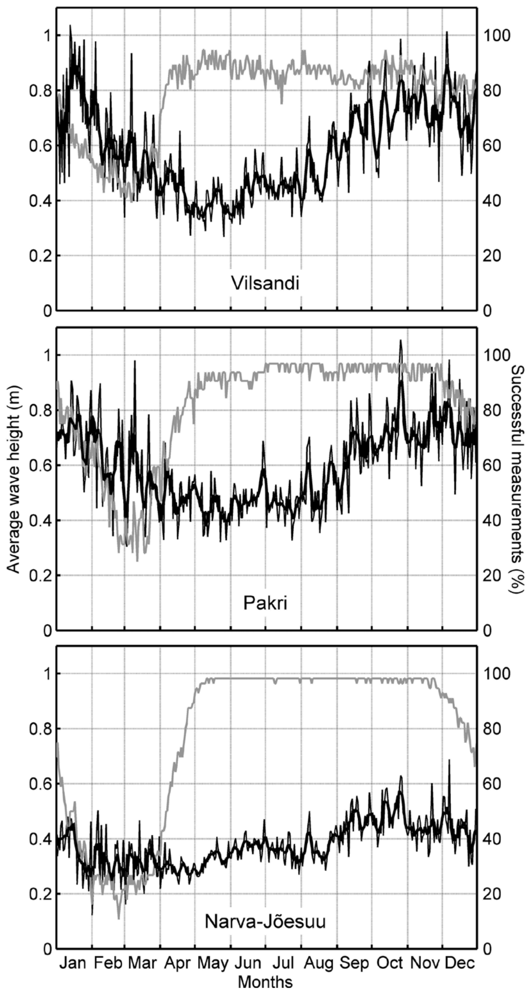

Fig. 4. Climatological mean wave heights at Vilsandi, Pakri and Narva-Jõesuu over all available wave observations (solid lines), their 5-day running averages (black) and the percentages of days with at least one successful observation on a given calendar day (grey). Data from 29 February are merged with data from 1 March.

This value is calculated for each calendar day over 55 years at Vilsandi and Narva-Jõesuu and over 31 years at Pakri. It eventually contains some noise, the level of which is the largest for the season when a relatively small number of measurements exist. Surprisingly, several short-time variations are synchronous at all three sites. This feature once more confirms that the results of visual observations give an adequate picture of wave statistics although single measurements may contain quite a large error.

The largest short-time feature in the wave activity is the relatively calm period at all sites at the end of December and the beginning of January. It can be clearly recognised from Vilsandi and Pakri data, and is somewhat less pronounced at Narva-Jõesuu. Short time periods with noticeably higher waves occur in all records during the first week of August, in the middle of September, at the end of October and at the beginning of December.

Long-term variations in wave heights

Long-term variations in wave conditions will be discussed below based on three sets of time series derived from wave observations, data from Almagrundet and numerically simulated time series. The analysis of the annual mean wave heights (called (overall) wave intensity below) obtained directly from the uncorrected daily mean values of observed wave conditions during a calendar year (Fig. 5) is complemented with analogous time series in which the missing measurements have been replaced by their climatological values for the same calendar day.

The reason behind the relatively large values of the annual mean wave height at Vilsandi in 1954–1956 is unclear. As the number of storm days was unusually large on the western coast of the Baltic Proper in these years (Bergström *et al*. 2001), such high wave intensity at Vilsandi may be real. Still we omit these years in the correlation analysis below.

All four time series of the annual mean wave heights based on visual observations and instrumental measurements in a calendar year show a reasonable match of years of relatively high and low wave intensity at all measurement sites in 1957–1986 (Fig. 5 and Table 2). Accordingly, there is a high correlation between annual mean wave heights at all sites in 1957–1986, with the correlation coefficients ranging from 0.44 to 0.53. The corresponding p-values are of the order of 0.01 or even smaller, indicating statistically significant correlation at 99% or higher level. The short-term interannual variability with time scales of 1–3 years had, therefore, the same appearance along the entire section of the Baltic

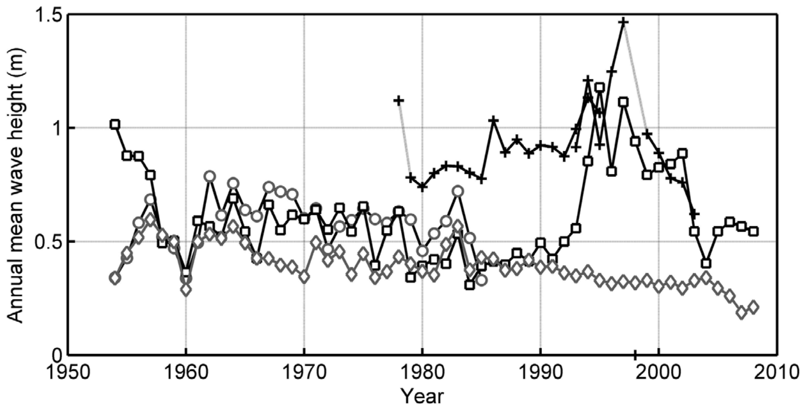

Fig. 5. Long-term variations in the annual mean wave height at Vilsandi (circles), Pakri (squares), Narva-Jõesuu (diamonds) and Almagrundet (crosses).

Sea coast from the Baltic Proper to Narva Bay in these years.

Interestingly, this coherence in the long-term variation in wave heights disappears abruptly at the end of the 1980s (Fig. 5 and Table 2). While the wave activity reveals a drastic decadal-scale increase and decrease in the Baltic Proper during the latter two decades, a gradual decrease in the annual mean wave height (0.4% per annum) is observed at Narva-Jõesuu. Differently from the period before the 1980s, years with relatively high wave intensity at Vilsandi correspond to relatively calm years in Narva Bay and *vice versa*.

This change is vividly expressed in terms of correlations between the observed and simulated annual mean wave heights (Table 2). It can seen in Fig. 5 that the coherence is abruptly lost starting from the year 1987; for this reason we compare below the course of wave heights in 1954–1986 and from 1987 onwards. The correlation between the time series for Vilsandi and Narva-Jõesuu is negative for 1987–2008 and the p value suggests that there is no correlation indeed.

A similar loss of correlation also occurs for the observed and numerically simulated time series of the annual mean wave heights. The correlation is statistically significant until about the year 1987 for all three sites but is much weaker (for Narva-Jõesuu) or virtually lost (for Vilsandi) since then (Table 3). This feature becomes even clearer in comparing simulated data with observed time series in which the missing observations are replaced by climatological mean values for the given calendar day (*see* below).

The described features indicate that certain substantial changes in wind properties apparently have occurred over the Baltic Sea since the mid-1980s. These changes, if real, have become evident as an increase in the wave intensity in areas open to southerly winds. They, however, have resulted in almost no changes in regions affected by waves approaching from the northern and western directions (cf. Kelpšaitė *et al*. 2009). Further, the described changes have occurred on the background of gradually increasing wind speeds in the Baltic Proper (Pryor and Barthelmie 2003, 2010, Broman *et al*. 2006). Consequently, such changes have mostly affected southern and SW winds.

This conjecture matches the results of the analysis by Kull (2005), who demonstrated that important changes to the directional structure

Table 2. Correlation coefficients between the annual mean wave heights at Vilsandi, Pakri and Narva-Jõesuu. The upper right cells show correlations for 1957–2008 (also separately for 1957–1986/1987–2008 for Vilsandi and Narva-Jõesuu); the lower left cells show the relevant p values.

Site	Vilsandi	Pakri	Narva-Jõesuu
Vilsandi	–	0.53	–0.14 (0.49/–0.25)
Pakri	$p = 0.0023$	–	0.44
Narva-Jõesuu	$p = 0.28$ (0.0028/0.47)	$p = 0.014$	–

of winds and wind properties have occurred over Estonia. Namely, during the last 40 years there has been a significant increase in the frequency of SW winds and a decrease in southern and eastern winds all over Estonia. Such a change may be responsible for a large part of the increase in wave activity in the nBP as it leads to a systematic increase in the typical fetch length in this basin. On the other hand, this change also explains well why the annual mean wave heights have been almost constant or even decreased in Narva Bay.

Variations in climatologically corrected wave heights

It is important to verify the adequacy of the observed wave data (especially from Vilsandi, which show drastic variations in wave heights in the late 1990s and at the turn of the millennium) against major sources of potential errors or biases in observations such as large gaps in the time series or substantial changes in the duration of ice cover in the vicinity of the observation site. There are large gaps in the observations from Vilsandi in 1991–2004 (Soomere and Zaitseva 2007). For example, there are no data for July–September 1990 and no wave observations were performed in August–December 1997. Also, there has been a steep decrease in the average number of days with ice in the entire Western Estonian Archipelago (Jaagus 2006). As the annual mean wave heights were calculated based on the average wave heights only over the days when at least one consistent wave observation was performed, the missing of data from relatively calm periods eventually lead to an overestimation of the annual mean wave height. Similarly, the missing of wave data from a windy season generally leads to an underestimation of the annual mean wave activity.

While the impact of the missing of data from summer seasons on the annual mean wave height is intuitively obvious, the impact of the gradual lengthening of the ice-free season may be more complicated. The ice cover on the coasts of the western Estonian Archipelago occurred from mid-November to mid-April in the past. The changes in the beginning and end of the ice season have been almost symmetric during the last century, with a slightly larger number of additional ice-free days in spring (Jaagus 2006). As December (which is mostly ice-free nowadays) is one of the windiest months and April (which is also largely ice-free now at Vilsandi) is one of the calmest months, this pattern of changes is not expected to lead to any large change in the annual average wave height. (This conjecture does not hold in terms of the total wave load on the coasts, which obviously increases with an increase of the length of the ice-free season.) Therefore, the correlation between the annual mean wave intensity and the

Table 3. Correlation coefficients, bias and standard deviation (SD) between numerically simulated and observed time series of the annual mean wave height at Vilsandi, Pakri and Narva-Jõesuu for the calendar years. The division of the data set into two sub-intervals is made so that the contrast in the relevant correlation coefficients is maximised.

	Uncorrected data			Climatologically corrected data		
	Correlation (*r*)	Bias (cm)	SD (cm)	Correlation (*r*)	Bias (cm)	SD (cm)
Vilsandi						
1970–2007	0.13	2.8	21.3	0.32	13.4	16.3
1970–1988	0.34	6.5	12.5	0.53	10.5	12.0
1988–2007	0.16	11.0	27.2	0.06	16.0	19.7
Pakri						
1970–1984	0.64	1.3	5.3	0.64	1.6	4.8
Narva-Jõesuu						
1970–2007	0.36	9.7	11.8	0.32	8.8	10.3
1970–1985	0.74	4.5	6.1	0.69	5.8	6.9
1985–2007	0.15	12.9	14.4	0.03	10.6	12.1

length of the ice season is mostly implicit and may simply reveal unfavourable conditions for ice formation either through an increased winter temperature or by the frequent presence of relatively high waves.

In order to eliminate part of potential distortions caused by the lack of data, we amended the recorded time series of wave heights with the use of the climatological mean values of the wave heights for each calendar day. Doing such a "climatological correction" introduces a certain amount of noise because of the character of seasonal variations of the daily mean wave height (Fig. 4). Compared with the option of replacing missing observations by the relevant climatological monthly mean values, the described method avoids a bias connected with gaps in data for the transitional months such as April and with above-discussed variations in the wave heights in weekly scales. Physically, introducing such a correction is equivalent to largely ignoring the ice cover. Consequently, the results should have a better match with the numerically simulated ones.

There is a clear divergence between the annual mean wave heights obtained from the observed time series and from the climatologically corrected time series at Vilsandi in 1970–1990 (Fig. 6). The climatologically corrected values differ by up to 30% from the relevant values based on original data. As expected, the corrected mean wave heights are larger for years with relatively low wave intensity and long ice cover (for example, in the 1970s). The corrected mean wave heights are by up to 20% smaller in the 1990s and at the turn of the millennium. As expected, the wave intensity in climatologically corrected time series is clearly smaller than according to the original data for extremely stormy years 1995 and 1997 (Fig. 6). The increase in the overall wave intensity at the beginning of the 1990s is smoother but still substantial in 1993–2002. The best estimate for the actual wave intensity apparently lies between the two values.

The two estimates for the annual mean wave heights differ much less for Pakri and Narva-Jõesuu (except for a few most recent years, Fig. 6). The largest difference becomes evident for Narva-Jõesuu starting from 2005. Interestingly, the original and corrected values almost exactly coincide for Vilsandi for these years.

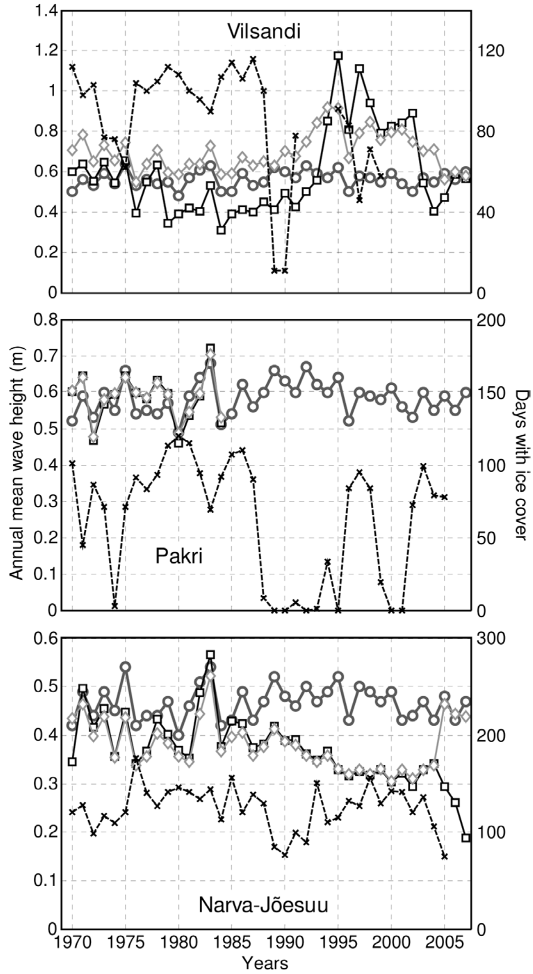

Fig. 6. Long-term variations in wave and ice conditions calculated based on calendar years at Vilsandi (upper panel), Pakri (middle panel) and Narva-Jõesuu (lower panel): original observed time series (squares), climatologically corrected time series (diamonds), numerically simulated time series (circles) and the length of ice season (crosses, estimated as the number of days from the first appearance of ice to the total disappearance of ice).

The climatological correction leads to a substantial increase in the correlation between simulated and observed annual mean wave heights (Table 3), in particular, for years of coherent observed and simulated interannual changes. This feature is not unexpected, because the presence of ice is ignored in simulations. On the contrary, the correlation between the simulated and observed values of the annual mean wave heights is completely lost for the years 1988–2007.

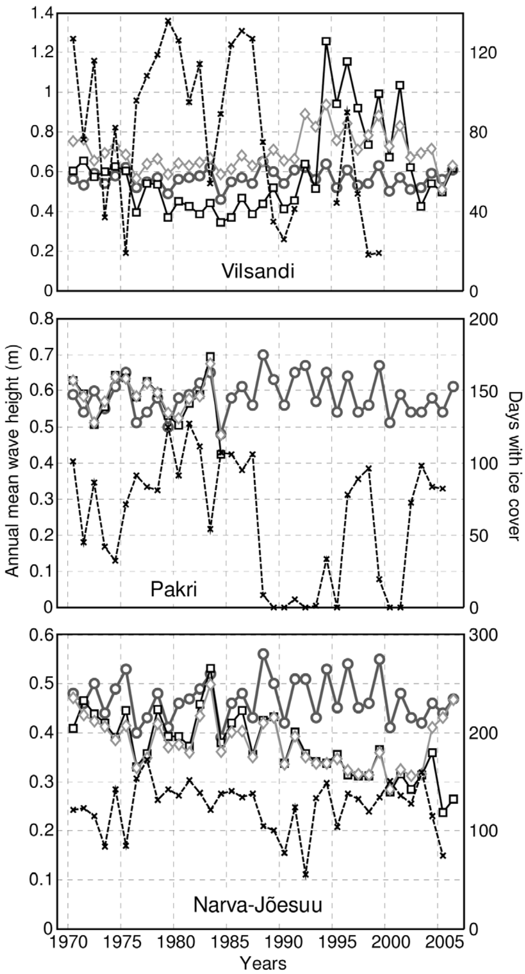

Fig. 7. Long-term variations in wave height over windy seasons (1 July–30 June of the subsequent year) at Vilsandi (upper panel), Pakri (middle panel) and at Narva-Jõesuu (lower panel). Notations are the same as for Fig. 6.

Filling the gaps with climatological values leads to a substantial increase in the difference of estimates of the long-term average wave intensity at Vilsandi. While for the original data the bias between the model results and observations was 2.8 cm, it increases to 13.4 cm for the amended data (Table 3). The increase in the difference is the largest for the years 1988–2007 for which the match of the observed and modelled data was the worst. The resulting bias is close to that obtained in the comparison of the measured and modelled data for Almagrundet (Räämet *et al*. 2009). This feature could be interpreted as additional evidence that the wind forcing in use in the wave hindcast leads to an overall slight underestimation of wave heights in the Baltic Proper.

Stormy and ice seasons

The time series of the annual mean wave heights presented above were calculated over two relatively windy time periods each year (January–February and September–December). As stormy seasons and periods with ice cover may occur during quite different months in different years (Sooäär and Jaagus 2007), comparisons based on calendar years may give somewhat distorted reflection of the severity of wave conditions in a particular autumn–winter windy season. A time series that more adequately reflects the overall wave conditions during different stormy seasons is that of the average wave height over periods covering the entire windy season (September–March), separated by a date corresponding to one of the lowest annual wave heights. For simplicity, below we consider the average wave height over periods 01 July to 30 June of the subsequent year calculated, as above, from the daily average observed wave heights.

The basic properties of long-term variations in the wave intensity at all the sites are the same as revealed by the time series over calendar years (Fig. 7). There is high interannual variation around the year 1960 in all the data sets, a period of relatively low wave intensity in the 1980s and a drastic increase in wave heights over the 1990s at Vilsandi.

The correlations between simulated and observed data are almost the same (albeit slightly lower) as for the data over calendar years for Pakri and Vilsandi (Tables 3 and 4). The similar correlations for Vilsandi are almost the same for the last two decades but considerably higher for the originally observed and simulated data for the entire period of simulations 1970–2007 and for climatologically corrected data for 1988/1989–2006/2007. This feature suggests that periods containing long-lasting rough seas are concentrated at Vilsandi in a few months whereas such periods may happen either in autumn or in winter. The WAM model and the forcing in use represent such periods. The analysis over calendar years apparently has a tendency to smooth out their contribution into the annual mean wave height by means of splitting them between subsequent calendar years. Interestingly, the simulated and observed wave heights move in antiphase for 1972/1973 at Pakri whereas all other changes are mostly in phase in other years both at Pakri and Narva-Jõesuu (Fig. 7).

One of the key features forming the wave fields is ice cover. The maximum area covered by ice in the Baltic Sea substantially varies between years (Bergström *et al*. 2001, Leppäranta and Myrberg 2009). For example, at Vilsandi the duration of ice cover may vary from a few to > 100 days during a winter (Fig. 6). The presence of ice may have a twofold impact on the observed wave data. First, fast ice makes wave observations impossible, leading to gaps in the time series. Second, an ice cover upwind from the observation site reduces the effective fetch length and thus the observed wave height and period. As the open part of the Baltic Proper does not freeze during "normal" winters, this effect is not likely to affect the predominant waves that approach Vilsandi from the ice-free SW direction. It may, however, damp the generation of waves during N-NW storms at all sites in question.

Typically, Estonian coastal waters are ice-covered from January to March (Sooäär and Jaagus 2007). The above analysis (Fig. 3) suggests that the absence of ice cover in January would generally lead to an increase in the annual mean wave height at Vilsandi and Pakri, but the absence of ice cover in February and especially in March–April would lead to its decrease. Comparison of the interannual variations in the mean wave height calculated from observations and from climatologically corrected data (Figs. 6 and 7) confirms this pattern of changes. The artificial "lengthening" of the ice-free period by inserting climatological values for the missing measurements leads to a clear increase in the annual mean wave height at Vilsandi in normal and relatively severe winters of 1975–1988.

In areas where the season of the potentially highest waves overlaps with the ice season (such as the eastern part of the Gulf of Finland where fast ice is frequently formed in November) the reduction of the ice season may lead to a drastic intensification of coastal processes (Ryabchuk *et al*. 2011). This process may be intensified to some extent by the presence of longer fetch in coastal areas of the NE Baltic Proper.

There is almost no difference between the annual mean wave heights calculated from the original and climatologically corrected data for Pakri and Narva-Jõesuu. Consequently, these areas are relatively calm in mild winters. This feature is not fully unexpected, because the more frequent presence of mild winters apparently occurs simultaneously with an increase in the frequency of SW winds (Kull 2005). Such winds generally excite large waves neither at Pakri nor at Narva-Jõesuu.

Table 4. Correlation coefficients, bias and standard deviation (SD) between numerically simulated and observed time series of the mean wave height at Vilsandi, Pakri and Narva-Jõesuu calculated for the time periods from 1 July to 30 June of the subsequent year. The separation into sub-intervals is the same as for Table 3.

	Uncorrected data			Climatologically corrected data		
	Correlation (*r*)	Bias (cm)	SD (cm)	Correlation (*r*)	Bias (cm)	SD (cm)
Vilsandi						
1970/1971–2006/2007	0.28	3.4	22.2	0.38	13.5	16.2
1970/1971–1988/1989	0.28	7.6	12.5	0.35	9.6	11.3
1988/1989–2006/2007	0.17	13.0	29.3	0.29	16.7	20.0
Pakri						
1970/1971–1984/1985	0.58	0.5	5.4	0.57	1.0	4.7
Narva-Jõesuu						
1970/1971–2006/2007	0.38	9.6	11.5	0.36	9.0	10.6
1970/1971–1985/1986	0.66	4.8	6.0	0.65	6.0	7.1
1985/1986–2006/2007	0.43	12.6	14.2	0.29	11.0	12.6

Finally, the analysed data show virtually no correlation between the annual mean wave height (optionally calculated over different time periods and/or with the use of climatologically corrected values) and the length of ice cover at the sites (Figs. 6 and 7). Although there is some qualitative match of these quantities in single years, the relevant correlation coefficient is well below 0.2 and no statistically significant correlation exists.

Discussion and conclusions

The data sets of visual wave observations from Estonian coastal sites Vilsandi, Pakri and Narva-Jõesuu cannot be used as an adequate approximation of the time series of the sea state because of their low temporal resolution. Yet the performed analysis suggests that the data represent well the general features of the wave fields in the northern Baltic Sea (Jönsson *et al*. 2002, Soomere 2008) such as a relatively low overall wave activity, short wave periods, and substantial seasonal and interannual variation of the wave conditions. The basic properties of the distributions of wave heights and periods and the overall mean and typical wave parameters largely follow the heuristically understandable patterns governed by the combination of the predominant strong winds and the geometry of the Baltic Sea. Especially Pakri data seem to reflect the open sea wave properties adequately.

Our analysis also revealed several intriguing features of wave fields in different coastal sections of the NE Baltic Proper and the Gulf of Finland. The most interesting outcome is a substantial change in the match of the long-term course in the wave activity in different coastal sections. The annual mean wave height showed nearly synchronous, substantial decadal-scale variations over the entire coastline of Estonia from the 1960s until the mid-1980s. Starting from the end of the 1980s, this coherence is lost and the temporal course of wave activity has been essentially decoupled in the northern Baltic Proper and the Gulf of Finland.

A minor feature, the nature and reliability of which are unclear, is that wave storms seem to be unevenly distributed in single months and there is an almost two weeks long relatively calm period around Christmas and the New Year.

Our analysis supports the impression that there has been a clear increase in the overall wave intensity in the northern Baltic Proper over the 1990s (Broman *et al*. 2006, Soomere and Zaitseva 2007). The increase in the annual mean wave height has been substantial, from about 0.5 m to the level of > 0.8 m, with a subsequent decrease to the level of the 1980s in 2005–2008. This pattern of changes is supported by the match of the data from Almagrundet and Vilsandi. It is somewhat surprising that simulations with the use of the high-resolution WAM model forced by adjusted geostrophic winds do not reveal these extensive variations although they do capture the short-term interannual variability of wave heights at Vilsandi, in particular, for the values calculated for the autumn-winter seasons. This feature deserves future detailed studies.

Another surprise was that no trend of increasing wave activity could be identified either in the northern Baltic Proper or at the entrance to the Gulf of Finland although the mean wind speed continues to increase over the area (Pryor and Barthelmie 2003, 2010, Broman *et al*. 2006). Moreover, the wave climate in the SE part of the Gulf of Finland is even characterized by a gradual decrease (0.4% per annum) in the wave height.

It is debatable what causes such mismatches and the loss of spatial coherence of the changes in the wave properties over the area studied. The changes in the ice conditions may have affected the course of wave activity at Vilsandi to some extent but evidently have no substantial influence on what was observed at Narva-Jõesuu as there have been virtually no changes in the beginning of the ice season (Sooäär and Jaagus 2007). A viable explanation is the radical change in the directional structure of moderate and strong winds – a substantial increase in the frequency of SW winds (Kull 2005, Jaagus 2009), which are able to excite high waves at both the eastern and western coasts of the northern Baltic Proper. Such changes affect only a limited part of the Baltic Proper and are consistent with analysis in (Kelpšaitė *et al*. 2008, 2009) that identified no substantial changes in wave heights in its southern sections and on the southern coast of the Gulf of Finland. The reasons behind the described patterns of changes evidently are not local and may be related to the shifts of the trajectories of cyclones (Alexandersson *et al*. 1998, Suursaar *et al*. 2006) or to certain changes in other parameters of the large-scale circulation.

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References

Alexandersson H., Schmith T., Iden K. & Tuomenvirta H. 1998. Long-term variations of the storm climate over NW Europe. *Global Atm. Ocean System* 6: 97–120.

Bergström S., Alexandersson H., Carlsson B., Josefsson W., Karlsson K.-G. & Westring G. 2001. Climate and hydrology of the Baltic Basin. In: Wulff F., Rahm L. & Larsson P. (eds.), *A systems analysis of the Baltic Sea*, Ecological Studies vol. 148, Springer, Berlin, Heidelberg, pp. 75–112.

Broman B., Hammarklint T., Rannat K., Soomere T. & Valdmann A. 2006. Trends and extremes of wave fields in the north–eastern part of the Baltic Proper. *Oceanologia* 48: 165–184.

Bumke K. & Hasse L. 1989. An analysis scheme for determination of true surface winds at sea from ship synoptic wind and pressure observations. *Bound. Lay. Meteor.* 47: 295–308.

Gulev S.K. & Hasse L. 1998. North Atlantic wind waves and wind stress fields from voluntary observing ship data. *J. Phys. Oceanogr*. 28: 1107–1130.

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

Häggmark L., Ivarsson K.-I., Gollvik S. & Olofsson P.-O. 2000. MESAN, an operational mesoscale analysis system. *Tellus* 52A: 2–20.

Jaagus J. 2006. Trends in sea ice conditions in the Baltic Sea near the Estonian coast during the period 1949/1950–2003/2004 and their relationships to large-scale atmospheric circulation. *Boreal Env. Res*. 11: 169–183.

Jaagus J. 2009. Pikaajalised muutused tuule suundade korduvuses Eesti läänerannikul. *Tallinna Ülikooli Ökoloogia Instituut. Publikatsioonid* 11: 11–24.

Johansson M., Boman H., Kahma K.K. & Launiainen J. 2001. Trends in sea level variability in the Baltic Sea. *Boreal Env. Res*. 6: 159–179.

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

Kahma K., Pettersson H. & Tuomi L. 2003. Scatter diagram wave statistics from the northern Baltic Sea. *MERI — Report Series of the Finnish Institute of Marine Research* 49: 15–32.

Kelpšaitė L., Herrmann H. & Soomere T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proc. Estonian Acad. Sci*. 57: 225–231.

Kelpšaitė L., Parnell K.E. & Soomere T. 2009. Energy pollution: the relative influence of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea. *J. Coastal Res*. Special Issue 56: 812–816.

Komen G.J., Cavaleri L., Donelan M., Hasselmann K., Hasselmann S. & Janssen P.A.E.M. 1994. *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambridge.

Kull A. 2005. Relationship between interannual variation of wind direction and wind speed. *Publicationes Instituti Geographici Universitatis Tartuensis* 97: 62–73.

Laanearu J., Koppel T., Soomere T. & Davies P.A. 2007. Joint influence of river stream, water level and wind waves on the height of sand bar in a river mouth. *Nordic Hydrol*. 38: 287–302.

Leppäranta M. & Myrberg K. 2009. *Physical oceanography of the Baltic Sea*. Springer Praxis, Berlin, Heidelberg, New York.

Mietus M. (co-ordinator) 1998. *The climate of the Baltic Sea Basin. Marine meteorology and related oceanographic activities*. Report 41, World Meteorological Organisation, Geneva.

Myrberg K., Ryabchenko V., Isaev A., Vankevich R., Andrejev O., Bendtsen J., Erichsen A., Funkquist L., Inkala A., Neelov I., Rasmus K., Rodriguez Medina M., Raudsepp U., Passenko J., Söderkvist J., Sokolov A., Kuosa H., Anderson T.R., Lehmann A. & Skogen M.D. 2010: Validation of three-dimensional hydrodynamic models of the Gulf of Finland. *Boreal Env. Res*. 15: 453–479.

Orviku K., Jaagus J., Kont A., Ratas U. & Rivis R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. *J. Coastal Res*. 19: 364–375.

Pettersson H. 2001. Aaltohavaintoja Suomenlahdelta. Suuntamittauksia 1990–1994. *MERI — Report Series of the Finnish Institute of Marine Research*, 44: 1–37.

Pettersson H. 2004. *Wave growth in a narrow bay*. Ph.D. thesis, Contributions no. 9, Finnish Institute of Marine Research.

Pettersson H., Kahma K.K. & Tuomi L. 2010. Predicting wave directions in a narrow bay. *J. Phys. Oceanogr*. 40: 155–169.

Pryor S.C. & Barthelmie R.J. 2003. Long-term trends in near-surface flow over the Baltic. *Int. J. Climatol*. 23: 271–289.

Pryor S.C. & Barthelmie R.J. 2010. Climate change impacts on wind energy: a review. *Renew. Sust. Energ. Rev.* 14: 430–437.

Räämet A. & Soomere T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Proper. *Estonian J. Earth Sci.* 59: 100–113.

Räämet A., Suursaar Ü., Kullas T. & Soomere T. 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *J. Coastal Res.* Special Issue 56: 257–261.

Räämet A., Soomere T. & Zaitseva-Pärnaste I. 2010. Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. *Proc. Estonian Acad. Sci.* 59: 182–192.

Ryabchuk D., Kolesov A., Chubarenko B., Spiridonov M., Kurennoy D. & Soomere T. 2011. Coastal erosion processes in the eastern Gulf of Finland and their links with long-term geological and hydrometeorological factors. *Boreal Env. Res.* 16 (suppl. A): 117–137.

Sooäär J. & Jaagus J. 2007. Long-term variability and changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proc. Estonian Acad. Sci. Eng.* 13: 189–200.

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

Soomere T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Env. Res.* 10: 103–118.

Soomere T. 2008. Extremes and decadal variations of the northern Baltic Sea wave conditions. In Pelinovsky E. & Kharif Ch. (eds.), *Extreme ocean waves*, Springer Verlag, pp. 139–157.

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

Soomere T. & Zaitseva I. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proc Estonian Acad Sci. Eng.* 13: 48–64.

Soomere T., Myrberg K., Leppäranta M. & Nekrasov A. 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia* 50: 287–362.

Suursaar Ü. 2010. Waves, currents and sea level variations along the Letipea–Sillamäe coastal section of the southern Gulf of Finland. *Oceanologia* 52: 391–416.

Suursaar Ü. & Kullas T. 2009. Decadal variations in wave heights off Cape Kelba, Saaremaa Island, and their relationships with changes in wind climate. *Oceanologia* 51: 39–61.

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

Suursaar Ü, Kullas T. & Szava-Kovats R. 2010. Wind and wave storms, storm surges and sea level rise along the Estonian coast of the Baltic Sea. *WIT Transactions on Ecology and the Environment* 127: 149–160.

Zaitseva-Pärnaste I., Suursaar Ü., Kullas T., Lapimaa S. & Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. *J. Coastal Res.* Special Issue 56: 277–281.

Paper V

Zaitseva-Pärnaste I., Soomere T., Tribštok O. 2011. Spatial variations in the wave climate change in the eastern part of the Baltic Sea. *Journal of Coastal Research*, Special Issue 64, vol I, 195–199.

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Spatial variations in the wave climate change in the eastern part of the Baltic Sea

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ABSTRACT

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The study presents new evidence of large spatial variations in wave properties along the eastern coast of the Baltic Sea. The short-term (1–3 years) interannual variability of the annual mean wave height is almost coherent along the entire eastern coast in 1958–1986. This coherence is completely lost from about 1987: since then the annual mean wave height at Narva-Jõesuu is in anti-phase with this height in the Baltic Proper. Also, in 1954–1957 the mean wave height in the eastern part of the Baltic Proper gradually decreases but rapidly increases in the Gulf of Finland. The decadal course of wave activity match relatively well each other at Nida and Vilsandi until about 1992, after which the annual mean wave height behavior is completely different at these sites. The largest difference between the long-term course in the wave height is found between Vilsandi (where the wave activity increases by a factor of two in 1987–1997 and decreases even more since then) and Narva-Jõesuu (where the wave activity gradually decreases over the entire observation period).

ADDITIONAL INDEX WORDS: *Wave climate, wave modeling, trends, climate change, Baltic Sea.*

INTRODUCTION

Wave climate and its changes are one of the key elements of physical oceanography and coastal science as wind waves are a major driver of coastal processes. Large changes in the wave climate are unlikely on the open ocean coasts where a substantial part of wave energy arrives in the form of swell waves (Dodet *et al*., 2010; Dragani *et al*., 2010). On the contrary, even small changes to the wind regime may easily lead to large variations in wave properties and extensive consequences for sedimentary beaches developing in fetch-limited conditions of semi-enclosed basins. For example, a change in the predominant wind direction may lead to a substantial increase in the typical fetch length in such basins. In this light, the wave climate is one of the most significant indicators of the changes in wind regime in semi-enclosed sea areas with complex geometry.

The temporal coverage of wave climate studies is usually limited by the length of existing wave time series. Typically, contemporary wave measurements begin from the 1970s. We discuss a unique data set of visual wave observations on the eastern coast of the Baltic Sea that goes back as long as to the mid-1950s. Its potential for the identification of the basic features of wave parameters and for the quantification of the seasonal cycle, inter-annual variations and long-term changes in the annual mean wave height (called wave activity below) has been discussed in (Soomere and Zaitseva, 2007; Kelpšaitė *et al*., 2008; Zaitseva-Pärnaste *et al*., 2009; Räämet *et al*., 2010). The analysis based on data from three observation sites on the north-eastern coast of the Baltic Sea has shown that the long-term course of the wave activity reveals no clear trend and has mostly a quasiperiodic nature, with the interval between subsequent periods of high or low wave activity about 25 years. The northern Baltic Proper was comparatively calm at the end of the 1950s, became slightly rougher in 1965–1975, and then calmer again at the end of the 1970s. A rapid increase in the annual mean wave height (well over 1% per annum) from the mid-1980s to the mid-1990s was replaced by a drastic decrease in the wave activity since 1997 (Broman *et al*., 2006; Soomere and Zaitseva, 2007). The increasing phase in the 1980s and the 1990s matches the analogous trend for the North Atlantic (Gulev and Hasse, 1999) whereas a subsequent decrease is consistent with the results of numerical simulations for the North Sea (Weisse and Günther, 2007). This course in wave activity is also consistent with the course of storminess over most of the North Atlantic and northern Europe. The storminess has gradually increased during most of the 20th century but this trend has ceased by the end of the 20th century (Alexandersson *et al*., 2000). Most of the described variations become evident in wave modeling efforts but the magnitudes of interannual and long-term variations are much larger in the visually observed data sets than in the numerically simulated ones (Suursaar and Kullas, 2009; Räämet *et al*., 2010; Suursaar, 2010).

In this paper, we extend the analysis of historical visually observed wave data to the SE part of the Baltic Sea. Based on a comparison of the existing data from the NE of the Baltic Sea with data from Nida on the coast of Lithuania, we present new evidence of large spatial variations in wave properties along the eastern coast of the Baltic Sea and of substantial decadal changes in the predominant wave propagation direction.

METHODS AND DATA

The analysis is based on four data sets recorded at (i) Nida at the northern part of Curonian Spit (1954–2009, 55°19′N, 21°01′E) in the south-eastern part of the Baltic Sea, (ii) the western coast of

Figure 1. Location scheme of the long-term wave observation points sites on the eastern coast of the Baltic Sea.

the Island of Vilsandi (1954–2008, 58°22′59″N, 21°48′55″E) in the Western Estonian archipelago, (iii) Pakri (1954–1985) in the NW part of the Gulf of Finland (59°23′37″N, 24°02′40″E) and (iv) Narva-Jõesuu in the eastern part of the gulf (1954–2008, 59°28′06″N, 28°02′42″E) (Figure 1).

Systematic wave observations at these sites started in 1954 and have been carried out until today (until 1985 at Pakri) with the use of an identical observation procedure. Observations at Nida reflect well waves approaching from the directions of the largest fetch (west and NW, Kelpšaitė *et al*., 2008). Data from Vilsandi reflect well waves coming from all westerly directions (Soomere and Zaitseva, 2007). Pakri is a relatively deep-water observation site on the southern coast of the Gulf of Finland (Zaitseva-Pärnaste *et al*., 2009). Waves at Narva-Jõesuu usually stem from the Gulf of Finland. The presence of a large river mouth allows wide range of wave approach directions for observations (Räämet *et al*., 2010).

The analysis of visually observed wave data from three Lithuanian sites (Nida, Palanga and Klaipėda) for 1993–2008 shows that the changes to the annual mean wave height occur almost synchronously at these sites. This is not unexpected as the sites are located on the open slightly curved section of the coast with a length of <100 km (Kelpšaitė *et al*., 2008) and spatial changes to the wave climate have a typical scale of at least 200 km for the Baltic Proper (Soomere and Räämet, 2010). For this reason, we interpret the data from Nida as representing the wave climate and its changes for the entire coast of Lithuania.

A description of the observation sites, the procedure of observations and the basic properties of the wave data from the Estonian coasts is presented in (Soomere and Zaitseva, 2007; Zaitseva-Pärnaste *et al*., 2009; Räämet *et al*., 2010; Soomere *et al*., 2011) and we give here only the key information. We only use wave height and approach direction from different observed wave properties. The observational procedure resembles the classical zero-crossing method. The observer noted the five highest waves during a 5-minute time interval and recorded the highest single wave (its height is called the maximum wave height) and the mean height of these waves. As the typical wave periods in the coastal zone of the Baltic Sea are 3–4 s (Broman *et al*., 2006, Räämet *et al*., 2010), the resulting mean wave height is approximately equal to the average height of 3–6% of the highest waves. As the observers' estimates represent the significant wave height well (Gulev and Hasse, 1999), the visually observed data are interpreted as estimates of the significant wave height in the earlier studies (Zaitseva-Pärnaste *et al*., 2009, Räämet *et al*., 2010, among others). As swells of substantial height are infrequent in the Baltic Sea (Broman *et al.,* 2006), the wave approach direction normally represents the direction of the windseas.

The site on Vilsandi reasonably reflects wave conditions for the predominant wind directions (SW and N-NW) in the northern Baltic Proper but gives inadequate data for easterly winds (which are relatively weak and infrequent in this area). As the water depth is only 4–5 m over the area where waves are observed, the highest waves may experience substantial impact of bathymetry and may be already breaking. For this reason, observations of the unreasonably high waves are discarded from the data set (Soomere and Zaitseva, 2007).

The observed wave properties represent well the open sea conditions for northerly wave directions particularly at Pakri. The average depth of the area over which the waves were observed was 8–11 m. Waves were observed from a steep cliff 24 m from the mean sea level. The Pakri data set contains the evidence of the roughest ever reliably recorded wave conditions in the Estonian coastal waters. Namely the wave height of 6 m was recorded twice each day on 6–7 August 1967 when a strong NW storm excited extremely rough wave conditions and caused extensive damage to the forests (Zaitseva-Pärnaste *et al*., 2009).

Narva-Jõesuu meteorological station is located on the coast of Narva Bay in the eastern part of the Gulf of Finland. The height of the observation platform (12.8 m above the mean sea level) allows good wave observation conditions over the area located about 200–250 m from the coast. The average water depth in this area is 3–4 m. As waves in the Gulf of Finland are generally much lower than in the Baltic Proper, waves normally do not break in the observation area. The geometry of the coastline at Nida allows proper observations of the wave parameters approaching from the western direction (from the west to N-NW). The observer was standing at a turret located 7 m above mean water level at the coast. The point at which the properties of waves were observed was located about 700 m from the coastline at a water depth of 6–7 m (Kelpšaitė *et al*., 2008).

Wave observations were only performed during daylight hours. The initial observation times in the 1950s and the 1960s (7:00, 13:00 and 19:00 Moscow time (GMT +3 hours)) were later shifted to 6:00, 12:00 and 18:00 GMT according to the WMO guidelines. This shift apparently has no substantial impact on the quality and homogeneity of the data. The potential bias in wave statistics related to the different number of observations per day in different seasons is eliminated by means of using the daily mean wave height at all sites.

There are several gaps in the data from Estonian sites from January to March apparently owing to the presence of sea ice. At least one sensible observation exists at these sites, in average, on about 80% of all the calendar days. The influence of the gaps on the overall wave statistics can be partially removed by means of filling the missing daily mean wave heights by the climatological values for the particular calendar day (Soomere *et al*., 2011). As this procedure only changes the magnitude of the trends but does not alter the overall course of the wave activity for the Estonian sites, we do not apply it here.

The low temporal resolution of visual observations means that they cannot be used for a reconstruction of the time series of the sea state. They are interpreted here as a set of regular samples reflecting the sea state. Since the number of observations is quite large, it is natural to expect that the data reflects the basic features of the wave climate at the site. All the observed and hindcast data sets reproduce the basic features of the northern Baltic Sea wave fields (Kahma *et al*., 2003; Soomere, 2008; Räämet and Soomere, 2010; Räämet *et al*., 2010) such as (i) the overall mildness of wave conditions with the long-term mean wave height in the open sea approximately 1 m and in the coastal areas 50–60 cm, (ii) a large proportion of wave conditions with the significant wave heights around 0.5 m, (iii) the most frequent peak periods 4–6 s in the open sea and 2–4 s in the nearshore regions, (iv) the match of the distribution of the most frequent combinations of wave heights and periods with fully saturated wave fields with the Pierson-Moskowitz spectrum and (v) strong seasonal variability in the Baltic Sea wave fields.

RESULTS

The basic properties of wave climatology at these sites match well the numerically simulated values (Räämet and Soomere, 2010). The monthly mean wave height at all sites follows the seasonal variation in wind speed in this region (Figure 2). At Estonian sites the maximum wave height is in October–January with a substantial variability on weekly scales. Seasonal variations of mean wave height at Nida coincide well with those at Estonian coast with May as the calmest and November as the roughest month. An unexpected feature of the seasonal course of wind speed and wave height in this region is that the windiest season is shifted by about 1–2 months with respect to the season with the largest wave activity (Räämet and Soomere, 2010).

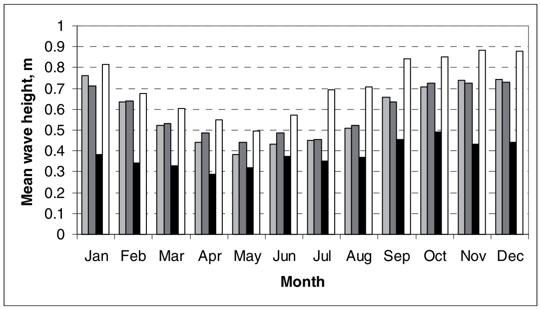

Figure 2. Seasonal variations in wave heights at Vilsandi (light grey bars), Pakri (dark grey bars), Narva-Jõesuu (black bars) and Nida (white bars).

Long-term behavior of wave fields

Although there is evidence about gradual increase in the mean wind speed over the Baltic Sea basin (Pryor and Barthelmie, 2003), there is no long-term increase in the annual mean wave heights at any of the observation sites on the eastern coast of the Baltic Sea. Moreover, the overall course of wave activity (Figure 3) reveals no clear long-term trend at the sites reflecting the wave conditions in the Baltic Proper (Nida, Vilsandi and partially Pakri). This feature is consistent with the results of long-term simulations of wave properties in the Baltic Sea basin based on geostrophic winds (Soomere and Räämet, 2010).

A clear decreasing trend in the wave activity is evident in Narva-Jõesuu data. This trend may be related to an asymmetric decrease in the length of the ice season in the Gulf of Finland mostly during relatively calm seasons (Sooäär and Jaagus, 2007) or, more probably, to a substantial increase in the frequency of SW winds over Estonia (Kull, 2009). This turn in wind directions means that the frequency of winds corresponding to very short fetches has considerable increased at Narva-Jõesuu. The related changes to the wave field become more clearly evident in the long-term course of the highest waves (Soomere *et al*., 2010).

Spatial pattern of quasiperiodic variations

Interestingly, a quasi-periodic variation with a typical time scale of 25–30 years can be identified in the longest data sets from the Baltic Proper (cf. Soomere and Zaitseva, 2007). An increase in the mean wave height at Vilsandi and at Pakri for a few years from the year 1960 and an overall slow decrease until the mid-1970s is observed at both sites.

The annual mean wave activity shows an interesting spatio-temporal pattern (Figure 3). The short-term (1–3 years) interannual variability is almost coherent at all sites in 1958–1986. In particular, variations in the wave activity at Pakri are the most similar to those at Vilsandi: there is almost perfect match of short-term variability in the annual mean wave heights and a high correlation coefficient (0.58) between these values in 1957–1985 at Vilsandi and Pakri. This coherence is completely lost from about 1987: since then the annual mean wave height at Narva-Jõesuu is in anti-phase with the height in the Baltic Proper. An analogous loss of coherence that is evident in 1954–1957 is discussed below in some detail.

The largest differences in the decadal course in the wave height become evident between Vilsandi (where the wave activity increases by a factor of two in 1987–1997 and decreases even more since then) and Narva-Jõesuu (where it gradually decreases over the entire observation period). There is even more drastic difference in the long-term behavior of the wave properties in the southern and northern parts of the Baltic Proper. Namely, the temporal course in the wave activity at Nida and Vilsandi match relatively well each other until about 1993. Further on the annual mean wave height behaves completely differently at these sites: there is a drastic decrease in the wave heights at Nida for 1990–1995 and a gradual increase starting from about 1996. This behavior becomes even more surprising when one compares it with the long-term changes to the wind speed in the northern Baltic Proper where the annual mean wind speed has gradually increased since the 1960s (Figure 4).

The newly presented data from Nida show the largest difference in the data from first three years of visual observations (1954–

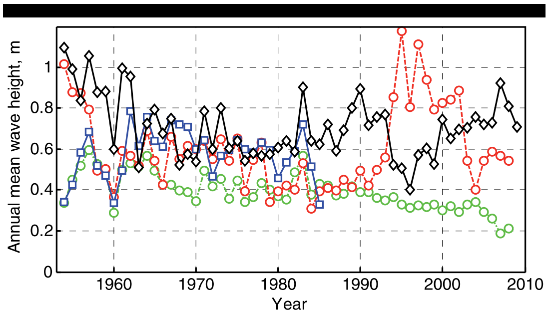

Figure 3. Annual mean wave height at Vilsandi (circles on dashed line), Pakri (squares) Narva-Jõesuu (grey circles) and Nida (diamonds). Notice that data from Pakri at 1985 do not contain information about the windiest season (October–December) and apparently underestimate the wave activity for this year.

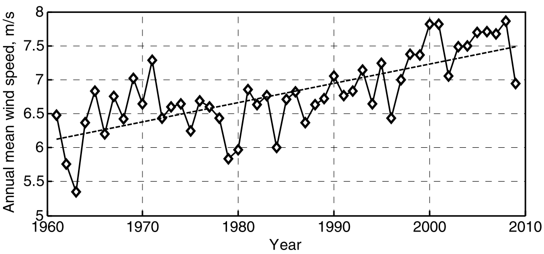

Figure 4. Long-term variations in the annual mean wind speed at Utö (1961–2009) and the relevant trendline. The average increase in the annual wind speed is 2.84 sm/s/year.

1956) in a new light. In the previous analysis the deviation in the wave height at different sites was related to a systematic overestimation of wave heights at Vilsandi during the first years of the observations (Soomere and Zaitseva, 2007). The rapid decrease in the wave activity in the Baltic Proper (at Nida and Vilsandi) in the mid-1950s is actually consistent with an analogous decrease in the number of storm days in the Baltic Sea region during the same period (Bergström *et al.*, 2001). The difference in the data from the Baltic Proper and the Gulf of Finland (reflected by data from Pakri and Narva-Jõesuu) may indicate an associated turn of the winds creating largest waves at different sites.

Changes in wave directions

It is natural to expect that the directional structure of approaching waves follows the prevailing winds and the geometry of the observation sites. This is particularly true for widely open sites such as Vilsandi (Figure 5) where a two-peak distribution of wave directions follows the well-know two-peak wind pattern in the northern Baltic Proper where strong winds blow from the SW or from N-NW (Soomere and Keevallik, 2001). The situation is different at more sheltered sites such as Nida or Narva-Jõesuu (Figure 4) where the fetch for some strong winds is very short. Waves mostly approach from the SW–NW direction at Nida and from a much wider range at Narva-Jõesuu.

The directional distributions of wave approach show a certain interannual and decadal variability for Vilsandi and Nida but reveal no substantial long-term changes of the predominant direction. The existing shifts and changes to this distribution in Figure 5 apparently are connected with the changes in the observation conditions such as a change in the observation site at Vilsandi (Soomere and Zaitseva, 2007).

The predominant wave directions have, however, exerted quite large changes at several observation sites whereas the contemporary wave models do not represent such turns (Räämet *et al.*, 2010; Kelpšaitė *et al.*, 2011).

For example, relatively small changes (but still substantially affecting the course of coastal processes) have been identified for the Lithuanian coast for the years 1993–2008 (Kelpšaitė *et al.*, 2011). The most pronounced changes in the predominant wave direction have occurred in Narva Bay (Figure 5) where the most frequent approach direction of waves has turned by more than 90° since the 1970s (Räämet *et al.*, 2010). Waves mostly approached from the W–NW direction until about 1965. The predominant approach direction moved almost to the north for the 1970s. Further on, it turned considerably, to the SW over the 1980s and has been mostly from the south within the latter decade. The most frequent observed propagation direction, therefore, has changed by more than 90° over the half-century of the observations (Räämet *et al.,* 2010).

DISCUSSION AND CONCLUSIONS

The performed analysis shows that interannual, decadal and long-term variations and trends may be completely different not only in different sub-basins of the Baltic Sea but also in different parts of its major body – the Baltic Proper. The switch from the in-phase behavior of short-term interannual variability in the wave activity around 1990 suggests that there has been a certain change in the nature of wind and wave storms in the entire Baltic Sea basin. While storms before 1990 have created high waves more or less simultaneously in the entire sea, since then stormy years in the Baltic Proper correspond to relatively calm years in the Gulf of Finland and *vice versa*. A more drastic difference in wave regimes

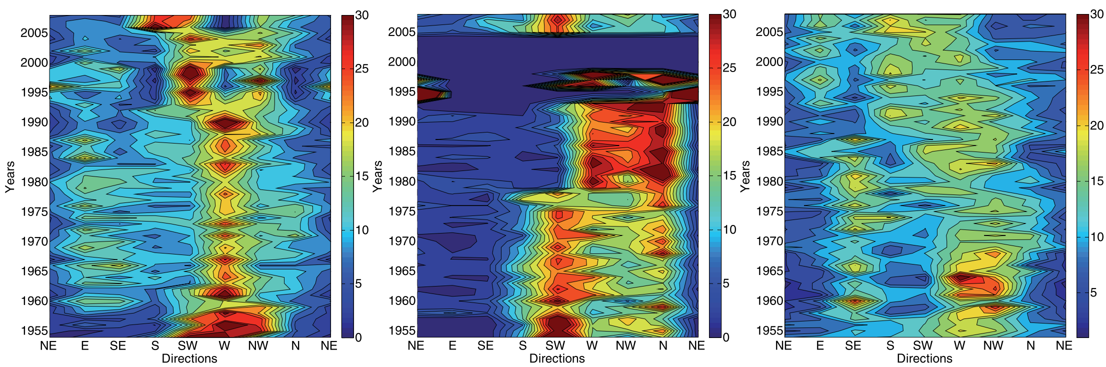

Figure 5. Temporal course in the directional distribution of wave approach directions at Nida (left panel), Vilsandi (middle panel) and Narva-Jõesuu (right panel, from Räämet *et al.*, 2010, with permission from the Estonian Academy Publishers) in 1954–2008 (% of all wave conditions in a calendar year). Notice that the number of recorded wave directions has decreased substantially at Vilsandi from 1992 and at Nida from 1998. The relevant distributions of different approach directions are not reliable for 1992/1998–2008. A shift in the distribution for Vilsandi at the end of the 1970s is apparently connected with a change in observation conditions.

becomes evident at the turn of millennia in the Baltic Proper.

While until the 1990s the decadal variations in the wave activity have been mostly similar for both the northern (Vilsandi) and southern parts (Nida) of this water body, these variations are completely different during the last two decades. There is a drastic decrease in the wave heights at Nida for 1990–1995 and a gradual increase starting from about 1996.

A probable reason for a part of the described changes is connected with gradual changes to the directional structure of predominant winds in the areas adjacent to the Gulf of Finland. The recent analysis by Kull (2005) shows that during the last 40 years there has been a significant increase in the frequency of SW winds and a decrease in southern and eastern winds all over Estonia. Such a change leads to a systematic increase in the typical fetch length for the northern part of the basin.

A highly interesting feature is that the gradual increase in the annual mean wind speed in most of the Baltic Sea basin (Pryor and Barthelmie, 2003) does not become evident in the long-term behavior of the annual mean wave height. This feature suggests that the Baltic Sea wave fields are more sensitive to other changes to the wind properties such as the change in wind direction and the corresponding change to the fetch length (Soomere *et al*., 2010). The discussed loss of coherence in the short-term interannual wave activity from the 1980s may be related with a shift of the typical trajectory of low-pressure systems over the Baltic Sea.

LITERATURE CITED

Alexandersson, H.; Tuomenvirta, H.; Schmith, T., and Iden, K., 2000. Trends of storms in NW Europe derived from an updated pressure data set. *Climate Research*, 14 (1), 71–73.

Bergström, S.; Alexandersson, H.; Carlsson, B.; Josefsson, W.; Karlsson, K.-G., and Westring, G., 2001. Climate and hydrology of the Baltic Basin. In: Wulff, F.; Rahm, L., and Larsson, P., (eds.), *A systems analysis of the Baltic Sea*, Ecological Studies, vol. 148, Springer, Berlin Heidelberg New York, pp. 75–112.

Broman, B.; Hammarklint, T.; Rannat, K.; Soomere, T., and Valdmann, A., 2006. Trends and extremes of wave fields in the north–eastern part of the Baltic Proper. *Oceanologia*, 48 (S), 165–184.

Dodet, G.; Bertin, X., and Taborda, R., 2010. Wave climate variability in the North-East Atlantic Ocean over the last six decades. *Ocean Modelling*, 31 (3–4), 120–131.

Dragani, W.C.; Martin, P.B.; Simionato, C.G., and Campos, M.I., 2010. Are wind wave heights increasing in south-eastern South American continental shelf between 32 degrees S and 40 degrees S? *Continental Shelf Research*, 30 (5), 481–490.

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

Kahma, K.; Pettersson, H., and Tuomi, L., 2003. Scatter diagram wave statistics from the northern Baltic Sea. *MERI – Report Series of the Finnish Institute of Marine Research*, 49, 15–32.

Kull, A., 2005. Relationship between interannual variation of wind direction and wind speed. *Publicationes Instituti Geographici Universitatis Tartuensis*, 97, 62–73.

Kelpšaitė, L.; Herrmann, H., and Soomere, T., 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proceedings of the Estonian Academy of Sciences*, 57 (4), 225–231.

Kelpšaitė, L.; Dailidienė, I., and Soomere, T., 2011. Changes in wave dynamics at the south-eastern coast of the Baltic Proper during 1993–2008. *Boreal Environment Research*, 16 (A), 220–232.

Pryor, S.C. and Barthelmie, R.J., 2003. Long-term trends in near-surface flow over the Baltic, *International Journal of Climatology*, 23 (3), 271–289.

Räämet, A. and Soomere, T., 2010. The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian Journal of Earth Sciences*, 59 (1), 100–113.

Räämet, A.; Soomere, T., and Zaitseva-Pärnaste, I., 2010. Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. *Proceedings of the Estonian Academy of Sciences*, 59 (2), 182–192.

Sooäär, J. and Jaagus, J., 2007. Long-term variability and changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proceedings of the Estonian Academy of Sciences. Engineering*, 13 (3), 189–200.

Soomere, T., 2008. Extremes and decadal variations of the northern Baltic Sea wave conditions. In: Pelinovsky, E. and Kharif, Ch. (eds.), *Extreme Ocean Waves*, Springer, pp. 139–157.

Soomere, T. and Keevallik, S., 2001. Anisotropy of moderate and strong winds in the Baltic Proper. *Proceedings of the Estonian Academy of Sciences. Engineering*, 7 (1), 35–49.

Soomere, T. and Räämet, A., 2010. Long-term spatial variations in the Baltic Sea wave fields. *Ocean Science Discussions*, 7, 1889–1912.

Soomere, T. and Zaitseva, I., 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proceedings of the Estonian Academy of Sciences, Engineering*, 13 (1), 48–64.

Soomere, T.; Zaitseva-Pärnaste, I.; Räämet, A., and Kurennoy, D., 2010. Spatio-temporal variations in the wind wave fields in the Gulf of Finland. *Fundamental and Applied Hydrodynamics*, 4(10), 90–101 (in Russian).

Soomere, T.; Zaitseva-Pärnaste, I., and Räämet, A., 2011. Variations in wave conditions in Estonian coastal waters from weekly to decadal scales. *Boreal Environment Research*, 16 (A), 175–190.

Suursaar, Ü., 2010. Waves, currents and sea level variations along the Letipea – Sillamäe coastal section of the southern Gulf of Finland. *Oceanologia*, 52 (3), 391–416.

Suursaar, Ü. and Kullas, T., 2009. Decadal variations in wave heights near the Cape Kelba, Saaremaa Island, and their relationships with changes in wind climate. *Oceanologia*, 51 (1), 39–61

Weisse, R. and Günther, H., 2007. Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958–2002. *Ocean Dynamics*, 57 (3) 161–172.

Zaitseva-Pärnaste, I.; Suursaar, Ü.; Kullas, T.; Lapimaa, S., and Soomere, T., 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. *Journal of Coastal Research*, Special Issue No. 56, Part 1, 277–281.

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Paper VI

Zaitseva-Pärnaste I., Soomere T. 2013. Interannual variations of ice cover and wave energy flux in the northeastern Baltic Sea. *Annals of Glaciology*, 54 (62), 175–182.

Interannual variations of ice cover and wave energy flux in the northeastern Baltic Sea

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ABSTRACT. The major factor shaping the coast of the micro-tidal Baltic Sea is wave activity, the impact of which is limited by the presence or absence of sea ice. Existing studies have revealed almost no correlation between the annual mean wave height and the duration of the ice season. We attempt to evaluate the correlation between ice season duration and bulk wave energy flux (wave power), mean energy and average wave height over the ice-free season for three segments of the Estonian coast (Vilsandi, Pakri and Narva-Jõesuu). Statistically significant correlation at the 95% confidence level exists between the duration of the ice season at Vilsandi (a site fully open to the predominant winds) and bulk wave energy flux derived from both observed and modelled wave properties. Similarly strong correlation exists between the mean wave energy and the duration of the ice season at the largely sheltered Narva-Jõesuu site.

1. INTRODUCTION

The Baltic Sea is a unique water body with many specific features. The major factor shaping its coast is wave activity. Although the Baltic Sea does not host significant tides, extensive variations in the water level (e.g. up to 4.21 m over the long-term mean in St Petersburg and up to 2.75 m in Pärnu) due to storm surges may occur in this water body (Suursaar and others, 2006; Schmager and others, 2008). Therefore, the particular impact region of waves and the intensity of coastal erosion may vary significantly during storm surges. Although the wave climate is relatively mild in this basin due to limited fetches, occasionally very strong wave storms may occur, with the offshore wave height reaching >9.5 m (Tuomi and others, 2011). The majority of the coast in the eastern part of the Baltic Sea exhibits overall sediment deficiency. This combination of occasional strong wave storms, high surges and sediment deficiency makes this area extremely vulnerable to any changes in hydrodynamics (Eberhards and Lapinskis, 2008; Kartau and others, 2011). In particular, the apparent increase in storminess during the second half of the 20th century (Alexandersson and others, 1998) is believed to be one of the key factors enhancing coastal erosion in this area (Orviku and others, 2003).

Recent studies have revealed a clear relationship between ice conditions and coastal processes. The absence of sea and coastal ice in some years generally means an increase in wave action in these years, which in turn usually leads to enhanced erosion of coastal areas of seasonally ice-covered seas (Overeem and others, 2011; St-Hilaire-Gravel and others, 2012). Changes in ice conditions also play a great role, comparable with that of changes in storminess, in the intensity of coastal processes in the Baltic Sea area (Orviku and others, 2003). The most drastic erosion events occur when late autumn and winter storms attack coastal sections that in more severe winters would be protected by ice cover (Ryabchuk and others, 2011). A common opinion is that climate changes in this area will generally lead to a reduction in the duration of the ice period (BACC Author Team, 2008) and thus to an increase in the total amount of wave energy reaching the nearshore and the coast. In this context, it is likely that rapid erosion in the recent past at certain locations that experience no direct anthropogenic impact (e.g. from coastal engineering structures) is associated with a combination of changes in the wave climate and a decrease in the duration of the ice season (Orviku and others, 2003; Ryabchuk and others, 2011).

The duration of the ice season varies substantially among different years and locations in the Baltic Sea (Leppäranta and Myrberg, 2009). This variation, together with seasonal variation in the wind and wave properties, may in single years greatly enhance the amount of energy supplied by waves to the nearshore. Previous studies of the interrelations of the wave climate and ice phenomena have focused on comparison of the variations in the annual mean wave intensity at the Estonian coast with changes in the duration of the ice season. These quantities did not reveal any correlation (Soomere and others, 2011). This result stems partially from a specific combination of seasonal variation in the wave heights and the ice period. The beginning of the ice season (late autumn) is characterized, on average, by the greatest annual wind speeds, whereas the end of the ice season (early spring) is one of the calmest periods of the year (Mietus, 1998). To a large extent, the shortening of the ice season occurs due to both the later appearance of the ice during the period of high wave activity and to the earlier disappearance of the ice during a relatively calm period. As a result, the annual average wave height over the ice-free season may remain almost unchanged (although the annual bulk wave energy flux to the coast may increase considerably). The associated problem of the construction of adequate wave statistics for seasonally ice-covered seas is extremely complicated (Kahma and others, 2003; Tuomi and others, 2011). Moreover, most of the rapid changes to the coast occur during a few severe wave storms (Orviku and others, 2003), the presence of which only weakly affects the annual mean wave height. This motivates us to search for a more appropriate but still simple measure that would be able to reflect, at least qualitatively, the potential impact of the change in the duration of the ice season.

A more adequate measure of wave-driven impact to the coast of seasonally ice-covered water bodies can be derived using the wave energy flux. This quantity is commonly

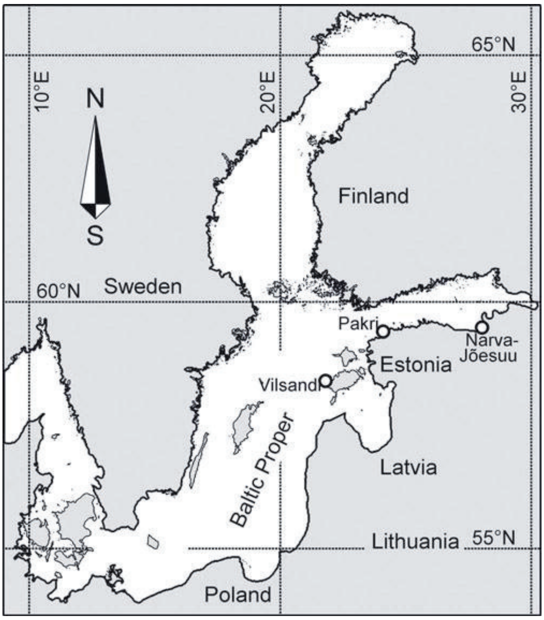

Fig. 1. Locations of the long-term coastal observation sites.

recognized as an acceptable measure of the instantaneous intensity of wave-driven alongshore sediment drift (USACE, 2002) in terms of the total amount of sediments that may be brought into motion during a certain time interval. We attempt to evaluate the correlation between the duration of the ice season and the total amount of wave energy flux (wave power) reaching the coast per ice-free season for selected segments of the Estonian coast. Other measures that may have the potential to quantify the role of ice in the coastal processes are the mean energy and the mean wave height in the ice-free period. All these quantities are calculated for time periods from July of a selected year until June of the subsequent year. The analysis is based on: (1) wave properties derived from visual observations during 1954–2005 at three observation sites; (2) numerical simulations using the third-generation spectral wave model WAM (Komen and others, 1994) for 1970–2005; and (3) data on the duration of the ice season for these sites. As a shorter ice season means a longer period during which the shoreline is exposed to waves, it is natural to expect that at least the total wave energy flux is strongly negatively correlated with the duration of the ice season, whereas the relationship between the average wave energy or the mean wave height and the duration of the ice season may be more complicated.

2. METHODS AND DATA

2.1. Visually observed wave data

An approximation of the time series of wave properties is derived from historical observations at three observation sites along the Estonian coast (Fig. 1): Vilsandi on the western coast of Estonia (1954–2005), Pakri at the entrance to the Gulf of Finland (1954–1985), and Narva-Jõesuu on the southeastern coast of the Gulf of Finland (1954–2005). The total number of single observations (one to three observations a day) ranges from about 20 000 at Pakri up to 40 000 at Vilsandi and Narva-Jõesuu. The routine, technical devices and methods for the visual wave observations performed at these sites, the major shortages and uncertainties connected with the resulting data and the pre-processing routines (to exclude the doubtful data) have been thoroughly discussed elsewhere (Gulev and Hasse, 1998, 1999; Soomere and Zaitseva, 2007; Soomere and others, 2011); therefore, here we present only a few key facts.

The data from Vilsandi reflect well waves coming from westerly directions. As the site is open to both the predominant strong wind directions (southwesterly and north-northwesterly) (Soomere and Keevallik, 2001), the dataset is thought to adequately represent long-term and decadal changes in the overall wave intensity in the northern Baltic Proper (Soomere and Räämet, 2011). Owing to relatively shallow water in the observation area (3–4 m), the filed wave heights in severe storms (with the significant wave height exceeding 3 m) do not properly represent the offshore wave heights. As the amount of such wave conditions is only ~1% in the northern Baltic Proper (Kahma and others, 2003; Broman and others, 2006; Soomere, 2008; Tuomi and others, 2011), the resulting distortions do not substantially alter the correlations under consideration.

Pakri is largely open to waves generated in the northern Baltic Proper but is sheltered from waves excited by the predominant southwesterly winds in this area. The observation site is located on the top of a high cliff, and the water depth in the measurement area is >10 m. Unfortunately, observations at Pakri are available only until 1985. Although the measurement site has been relocated several times during 1954–85, the seasonal and interannual variations in wave properties (which are decisive in the estimates of correlations with the ice data) are still adequately represented. A comparison with modelled data (Soomere and others, 2011) reveals that this site at best reproduces the properties of offshore wave fields.

The Narva-Jõesuu observation site is located on the southeastern coast of the Gulf of Finland in the wide and open Narva Bay. This site is open to the waves approaching from the west to north and also satisfactorily represents waves approaching from the southwest and north-northeast. Although the water depth at the observation domain was relatively small (~4–5 m), wave heights and periods were normally moderate and the depth-induced effects were reasonable. The wave observation procedure was identical at all three sites and did not change significantly throughout the years of observation (Soomere and others, 2011).

2.2. Simulated data

We use hourly time series of wave properties, extracted for the three sites in question, from numerical simulations of the Baltic Sea wave fields for 1970–2007 (Räämet and Soomere, 2010). They used the WAM wave model with an extended frequency range up to ~2 Hz (wave periods down to 0.5 s, 42 frequency bins) and a spatial resolution of ~3 nautical miles in idealized ice-free conditions. The reliability of simulated changes in the wave properties crucially depends on the homogeneity of the wind information in time. Although contemporary high-resolution atmospheric models such as the High Resolution Limited Area Model (HIRLAM) represent well the wind details at particular locations, their continuous development often leads to substantial inhomogeneities of their output in time (e.g. Tuomi and others, 2011). Thus, the use of winds that have possibly lower spatial resolution but that are maximally homogeneous in time (such as geostrophic wind fields that are derived from patterns of atmospheric pressure) is preferable to identify the long-term changes in wave properties.

The WAM model was driven by geostrophic winds with a spatial resolution of 1° and temporal resolution of 3 or 6 hours obtained from the Swedish Meteorological and Hydrological Institute. The geostrophic wind speed was multiplied by 0.6 and the direction turned 15° anticlockwise to yield an estimate of the surface wind at the 10 m level (cf. Bumke and Hasse, 1989). This approximation of the vertical structure of wind properties is frequently used in the Baltic Sea region. Although it completely ignores the stability questions of the atmospheric stratification, it leads to an acceptable reproduction of circulation patterns (Myrberg and others, 2010). The simulated wave properties satisfactorily replicate the time series of measured wave data (Räämet and others, 2009) and reproduce well the statistical properties of the wave fields at the observation sites in question (Soomere and others, 2011). A thorough comparison of the modelled and observed wave data was performed by Soomere and Räämet (2011).

2.3. Ice data

During each winter the coastal areas of the northern Baltic Sea are covered by landfast ice, which reaches depths of 5–15 m depending on the severity of the winter. Further out drift-ice fields are found (Leppäranta, 1981). Observations of ice properties in the nearshore zone of Estonia started in the 1800s at several lighthouses and have been performed systematically at several locations by the Estonian Meteorological and Hydrological Institute (EMHI) since the mid-20th century. The ice data include the dates of the first freezing, the formation of permanent ice cover, the end of permanent ice cover and the final disappearance of the ice and, optionally, the thickness of the ice cover (Jevrejeva and Leppäranta, 2002). The date of the first freezing (the first appearance of sea ice) is registered when ice of any type is first observed (Sooäär and Jaagus, 2007).

For the analysis we used ice data from the same three coastal observation sites run by the EMHI. The duration of the ice season was estimated for each site and winter as the number of days, from July to June of the subsequent year, between the day of the first appearance of the ice cover and that of the total disappearance of the ice. Similar to historical visual wave observations, ice observations have extensive gaps and uncertainties. Since the wave observations used in this paper were made for areas located at some distance from the shore and wave parameters were estimated even with the presence of drifting ice and limited amounts of ice features near the coast, the information about ice cover in the historical data does not exactly match the information about wind waves. On many occasions quite high waves have been recorded within the formal ice season as defined above. Such events are ignored in the calculations below.

As a first approximation we assume that: (1) the first appearance of the ice is associated with the freezing of onshore ground in potential areas of coastal erosion; and (2) these potentially erodible coastal sediments are frozen until the ice has completely disappeared. Assumption (1) is natural because the upper layer of the dry land loses heat much faster than the water column and supposedly freezes first. The soundness of assumption (2) is not crucial as the spring is usually very calm in the study area. These

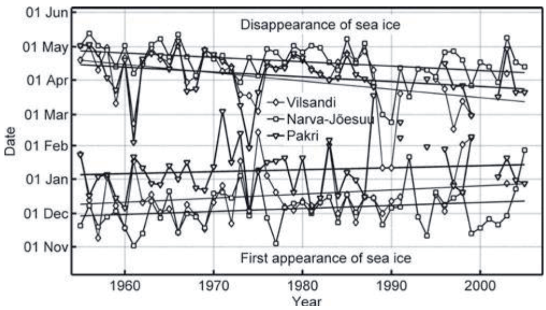

Fig. 2. The date of the first appearance of sea ice and the disappearance of sea ice at Vilsandi, Narva-Jõesuu and Pakri.

assumptions are equivalent to ignoring the wave impact during the entire ice season as described above. The ice datasets also have some gaps. For example, the relevant information is missing for Vilsandi in the periods 1992–94, 2000–02 and 2004–05 and for Pakri in the periods 1989–90, 1992–93, 1995, 2000–01. These years are excluded from the correlation analysis below.

The ice season in the study area usually lasts from November to May (Jevrejeva and Leppäranta, 2002; Sooäär and Jaagus, 2007). Figure 2 shows the day of the first appearance and day of the total disappearance of sea ice at Vilsandi, Narva-Jõesuu and Pakri. The duration of the ice season varies substantially at Vilsandi and Pakri. At Vilsandi the duration of the ice season (average 106 days and standard deviation (SD) 40 days) varies from 19 in 1975 to 180 in 1966 (Fig. 3) and at Pakri (average 85 days, SD 33 days) from 9 to 137 in 1988 and 1956, respectively. The variations are less at Narva-Jõesuu where the average duration of the ice season is 133 days (SD 26 days) and the duration varies from 55 days in 1992 to 178 days in 1966. The trend lines in Figure 2 suggest that an overall warming has occurred at the observation sites in question where the number of ice days has generally decreased during the last 50 years (1954–2005). While in the more sheltered Gulf of Riga (Sooäär and Jaagus, 2007) and at Vilsandi the duration of the ice season has decreased considerably over the last half century, the changes in some other coastal regions (Pakri and Narva-Jõesuu) are somewhat smaller. Several years with a very short ice season occurred around 1990 and at the beginning of the 2000s.

2.4. Estimates of wave energy and power

The experience with the visual observations shows that an observer's estimate of the wave height represents well the significant wave height (Gulev and Hasse, 1998, 1999). For that reason we interpret the observed wave height as an estimate of the significant wave height (Soomere and Zaitseva, 2007). As on many occasions wave observations were not performed in late autumn and winter, the missing data were replaced by their climatological mean values for each calendar day calculated over 52 years of observations (Soomere and others, 2011).

We calculated correlations for three different parameters characterizing the wave intensity and potential impact over the time period from 1 July to 30 June of the subsequent year: (1) the total wave energy flux reaching the coast during the ice-free period (called bulk wave power) (Fig. 3); (2) the mean wave energy over the ice-free period (Fig. 4); and

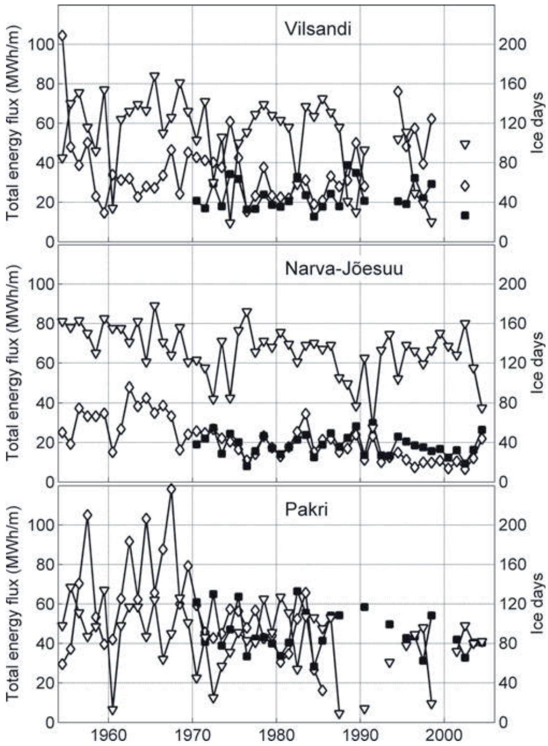

Fig. 3. Long-term variations in ice season duration (triangles) and the total energy flux during the ice-free season (diamonds and squares) at Vilsandi, Narva-Jõesuu and Pakri calculated over the time period from 1 July to 30 June of the subsequent year. Diamonds and squares indicate estimates of the energy flux derived from wave observations and simulated data, respectively.

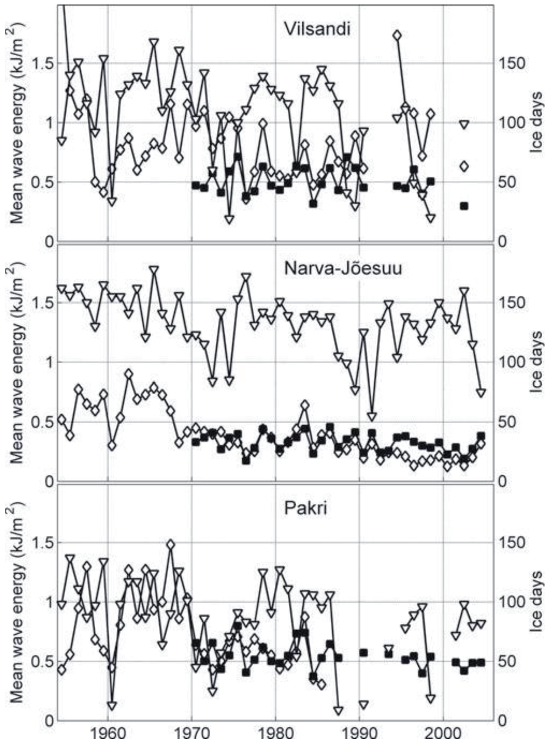

Fig. 4. Long-term variations in ice season duration (triangles) and the mean wave energy during the ice-free season (diamonds and squares) at Vilsandi, Narva-Jõesuu and Pakri calculated over the time period from 1 July to 30 June of the subsequent year. Notations are the same as in Figure 3.

(3) the mean wave height over the ice-free period (Fig. 5). The first parameter in the list is usually thought to be decisive for coastal processes.

The calculations of the wave energy and its flux were carried out using the same scheme for both observed and simulated wave properties. Since the water depth d at the observation sites and at the corresponding gridpoints of the wave model was quite small (4–7 m), the instantaneous values for the wave energy flux (wave power)

$$P = Ec_g \tag{1}$$

were calculated using the long-wave approximation $c_g = \sqrt{gd}$ for the group speed and the classical notion for wave energy E

$$E = \frac{\rho g H^2}{8}, \tag{2}$$

where H is the observed wave height for calculations based on the results of visual observations or for the modelled significant wave height for calculations using the WAM model output, g is the acceleration due to gravity and ρ is the density of sea water. The resulting values of wave energy and power were interpreted as representing the entire time interval between subsequent observations (or between instants for which the WAM model output was saved) and averaged (E) or summarized (P) over the ice-free season.

In calculations of the listed quantities we ignored all visually observed and numerically simulated wave properties that fell into the ice season (as specified above) for a particular year. Doing so properly accounts for the presence of sea ice in visually observed data but may to a certain extent underestimate the impact of waves just before the beginning of the ice season (e.g. in situations when a little ice is found in sheltered domains but the open sea is largely ice-free). As the wave modelling has been performed for ice-free sea, the wave properties for partially ice-covered situations are overestimated. The resulting errors in the estimates obviously affect the particular values of the mean wave energy and bulk wave power for single years, but do not substantially impact the level of correlations between the integral properties of wave fields and the duration of the ice season.

Similar to the duration of the ice season, all three parameters exhibit quite large variations in single years: the standard deviation of the annual values is typically 40–50% for the observed wave properties and 20–30% for the modelled data (Table 1).

3. RESULTS

Previous studies suggest that the annual mean observed wave height (even if amended using the climatological values) and the similar modelled wave height do not reveal a

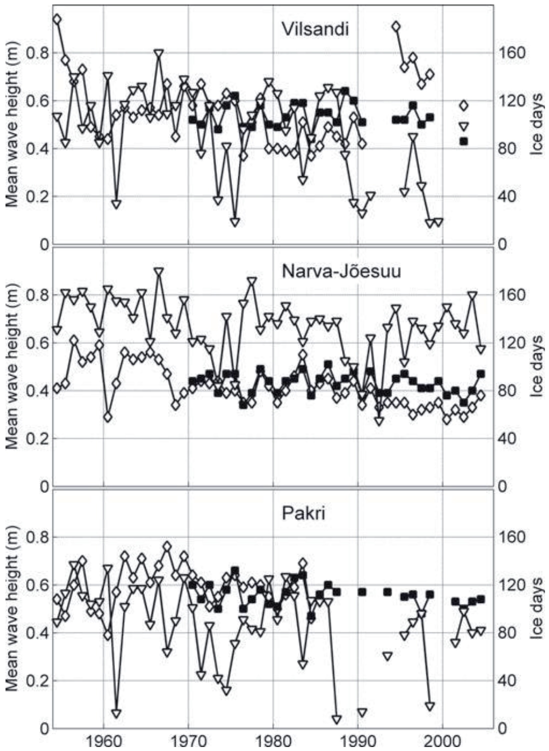

Fig. 5. Long-term variations in ice season duration (triangles) and the mean wave height during the ice-free season (diamonds and squares) at Vilsandi, Narva-Jõesuu and Pakri calculated over the time period from 1 July to 30 June of the subsequent year. Notations are the same as in Figure 3.

significant correlation with the duration of the ice season (Soomere and others, 2011). A likely reason for this is the aforementioned combination of the ice season and the annual course of wave activity: high waves occur in autumn and winter just before the ice season starts and relatively calm seas dominate in spring (Soomere and others, 2011).

Comparison of the measures of wave energy and its flux with the ice data first reveals that the short-term interannual variations in the bulk wave power are, as expected, mostly in counter-phase with the duration of the ice cover (Fig. 3). Given the definition of the bulk wave power, it is natural that long ice-free autumns correspond to large annual values of this measure while long ice seasons correspond to its relatively low values. The data from Vilsandi reveal statistically significant negative correlation at a >95% confidence level between the duration of the ice season and the bulk wave power, for both visually observed and numerically simulated wave time series (Table 2). A similar significant correlation exists between the length of the ice season and numerically simulated data for Pakri and Narva Jõesuu. Virtually no correlation exists between the length of the ice season and visually observed data. This discrepancy evidently reflects problems with insufficient temporal resolution of visual observations that are often only possible once a day during the windiest season just before ice formation.

The absence of any statistically significant correlation between the mean wave energy and the length of the ice season for both datasets at Vilsandi and Pakri is not surprising because the mean energy only implicitly reflects the variations in the duration of ice cover. The presence of such a strong correlation at Narva-Jõesuu for both the visually observed and modelled wave datasets may reflect the differences in the degree of openness of the three sites to the predominant southwesterly and north-northwesterly winds in the northeastern Baltic Sea. The nearshore of

Table 2. Correlation coefficients (*r*) and the relevant *p* values between the number of days with observed ice phenomena and the bulk energy flux, mean energy and mean wave height derived from numerical simulations and historical visual observations at Vilsandi, Narva-Jõesuu and Pakri. Statistically significant correlations at the >95% confidence level are indicated in bold

	Observations and the duration of the ice season		Simulations and the duration of the ice season	
Site	*r*	*p* value	*r*	*p* value
	Bulk energy flux in the ice-free period			
Vilsandi	**–0.406**	**0.007**	**–0.746**	**0.000**
Narva-Jõesuu	0.072	0.616	**–0.765**	**0.000**
Pakri	–0.038	0.835	**–0.577**	**0.001**
	Mean energy in the ice-free period			
Vilsandi	–0.078	0.620	–0.333	0.090
Narva-Jõesuu	**0.277**	**0.050**	**–0.461**	**0.005**
Pakri	0.165	0.366	–0.133	0.500
	Mean wave height over the ice-free period			
Vilsandi	–0.120	0.445	**–0.399**	**0.039**
Narva-Jõesuu	0.175	0.220	**–0.489**	**0.003**
Pakri	0.088	0.631	–0.204	0.298

Table 1. Average values and standard deviations of the bulk energy flux, mean energy and mean wave height in the ice-free period

Site	Bulk energy flux		Mean energy		Mean wave height	
	MWh m^{-1}	SD	kJ m^{-2}	SD	m	SD
	Visually observed data					
Vilsandi	37.1	17.0	851	349	0.56	0.14
Pakri	57.2	23.9	732	298	0.59	0.09
Narva-Jõesuu	21.3	10.2	391	199	0.41	0.09
	Numerically simulated data					
Vilsandi	23.1	7.2	505	111	0.53	0.05
Pakri	45.9	10.7	543	105	0.56	0.05
Narva-Jõesuu	18.7	5.3	325	73	0.43	0.04

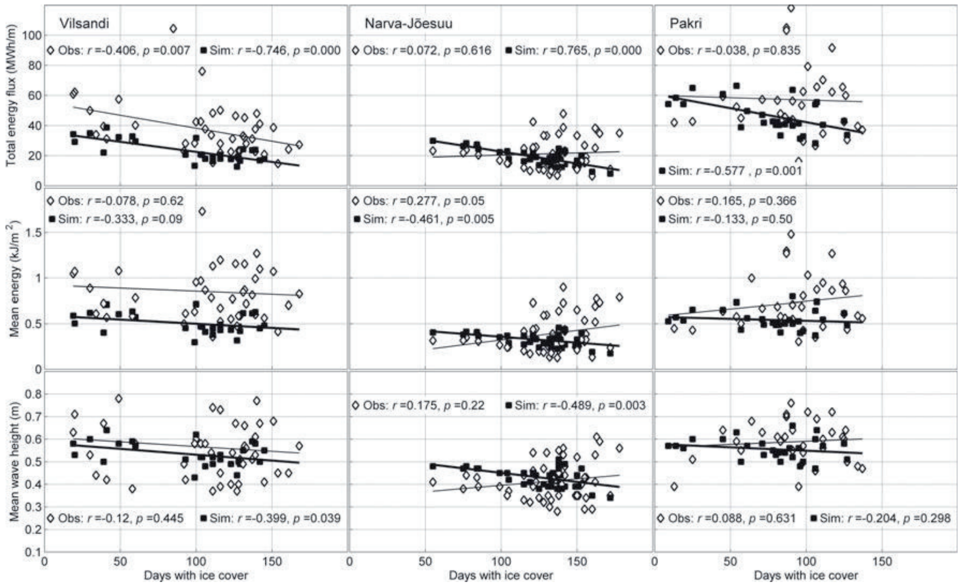

Fig. 6. Scatter diagram and regression lines for the bulk energy flux, mean energy and mean wave height during the ice-free period and the duration of the ice season (days). The quantities estimated from wave observations and simulations are indicated by diamonds and squares, respectively, and the relevant regression lines are regular and bold, respectively. Here *r* indicates the correlation coefficient and *p* shows statistical significance of the correlation (95% confidence level corresponds to $p < 0.05$).

Vilsandi is almost fully open to both southwesterly and north-northwesterly winds, and the ice regime at this site is strongly affected by storms. Pakri is open to north-northwesterly winds but is partially sheltered against waves excited by southwesterly winds. Narva-Jõesuu is mainly sheltered against waves excited by southwesterly winds, and north-northwesterly winds do not play any substantial role in the eastern Gulf of Finland (Soomere and Keevallik, 2003). Therefore, ice formation in this area is governed much less by the direct impact of rough seas or by the indirect impact of waves through mixing of the upper layer.

Differing from the annual mean wave height (Soomere and others, 2011), the modelled average wave height H_a over the ice-free season at Vilsandi and Narva-Jõesuu also shows a high negative correlation (statistically significant at the 95% confidence level) with the duration of the ice season (Table 2). This feature is apparently connected with the above-discussed asymmetry of the ice season with respect to the seasons with high and low wave intensity at these sites and once more signifies that the outcome of visual wave observations should be interpreted with great care. Similarly to the mean wave energy, also H_a reveals no correlation with the duration of the ice season at Pakri. As both ice and wave data cover only a part of the entire time interval in question at Pakri, the results for this site should be interpreted as indicative.

The features discussed are illustrated using scatter plots in Figure 6. In Figure 6 time series that show statistically significant correlation are aligned along certain (regression) lines, whereas the data form clouds of undefined shape if the correlation is weak. Note that the slope of the relevant regression lines for the observed and simulated data is almost the same for the measures and sites that reveal statistically significant correlation, whereas these slopes are very different (even in sign) for pairs of weakly correlated parameters.

4. CONCLUDING REMARKS

As mentioned in Section 1, it would be natural to expect that mean wave energy and especially bulk wave power are strongly negatively correlated with duration of ice season. The key finding of our study is that this is not always the case at the coast of the northeastern Baltic Sea. The correlation between the key wave properties calculated over the ice-free season (the mean energy, bulk wave power and average wave height) and the duration of the ice season is highly dependent on the particular site. At Vilsandi, as expected, this correlation is negative and statistically significant at the 95% confidence level for all modelled wave properties in question but is only evident for the bulk wave energy flux in case of observed wave data. This site is completely open to both the predominant wind directions in the northeastern Baltic Proper. The data from Narva Jõesuu on the south-eastern coast of the Gulf of Finland reveal statistically significant correlation between the duration of the ice season and the mean wave energy and also for the numerically simulated mean wave height. The correlation is practically absent at Pakri. The differences are most likely caused by the differences in the degree of openness of the three sites to the predominant winds.

Similarly to earlier studies, it is evident that the average wave height over the ice-free season usually does not have any statistically significant correlation with the duration of the ice season and thus should not be used as an appropriate measure to characterize the severity of the ice season and/or the impact of waves upon sedimentary coasts. The mean wave energy and especially the bulk energy flux seem to have a larger potential in this respect.

The established correlations should be interpreted with care because the total erosion rate in a particular coastal section is a complicated function of the wave properties and water level throughout the ice-free period. A decrease or increase in the ice season length would only diminish or enhance the erosion rate if the wave properties during the extension of the ice-free period are unfavourable. This is not necessarily the case in the northeastern Baltic Sea where major decadal changes in wave heights and approach directions have been observed since the 1950s (Soomere and Räämet, 2011).

A factor potentially affecting the level of the correlations is that the wave modelling has been performed for ice-free sea. The resulting bias in the estimates of wave properties for a partially ice-covered sea evidently affects the results to some extent. However, the strong correlations between the integral properties of wave fields and the duration of the ice season, especially at Vilsandi, are not substantially affected by this shortage. More detailed wave calculations with higher-resolution wind fields and using the offshore ice data are underway and will be reported elsewhere.

The demonstrated differences between the levels of correlations at different sites suggest that the duration of the ice season and the wave intensity may have complicated interrelations depending on the openness of a particular site to the waves excited by predominant winds. The established strong correlation at Vilsandi formally supports the intuitively obvious conjecture that higher levels of bulk wave power correspond to shorter ice seasons. The virtual absence of such correlations at other discussed observation sites indicates that in some situations ice formation and melting is virtually independent of wave activity. This feature should be carefully accounted for in the estimates of the impact of potential warming on the intensity of coastal processes. Namely, the obvious convenient measures for wave-driven impact on the coast, such as the total wave energy flux, may be completely uncorrelated with the changes in ice conditions.

This research focuses on the potential direct ice-driven limitations of the impact of waves on coastal processes and omits several indirect but still equally important effects of coastal ice. Firstly, we have ignored virtually all properties of ice and relied only on the duration of the ice period. In many instances, extensive ice-driven erosion and ice ride-up on the coast may mobilize sediments or destroy dune vegetation (Leppäranta, 2013). Somewhat less visible processes are bottom scouring and transport of large boulders. These effects usually occur irregularly. Although they are definitely caused by specific wind conditions, there seems to be no way to relate them to wave activity (except for specific cases when thin coastal ice is destroyed and piled up on a coast by a strong late autumn storm). Also, the additional forces to the ice edge exerted by wave-driven mass and momentum transport are often decisive for ice formation and destruction but are negligible compared with the wind impact over the entire ice sheet in terms of ice drift.

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REFERENCES

Alexandersson H, Schmith T, Iden K and Tuomenvirta H (1998) Long-term variations of the storm climate over NW Europe. *Global Atmos. Ocean Syst.*, **6**(2), 97–120

BACC Author Team (2008) *Assessment of climate change for the Baltic Sea basin*. Springer, Berlin

Broman B, Hammarklint T, Rannat K, Soomere T and Valdmann A (2006) Trends and extremes of wave fields in the north-eastern part of the Baltic Proper. *Oceanologia*, **48**(S), 165–184

Bumke K and Hasse L (1989) An analysis scheme for determination of true surface winds at sea from ship synoptic wind and pressure observations. *Bound.-Layer Meteorol.*, **47**(1–4), 295–308 (doi: 10.1007/BF00122335)

Eberhards G and Lapinskis J (2008) *Processes on the Latvian coast of the Baltic Sea*. University of Latvia, Riga

Gulev SK and Hasse L (1998) North Atlantic wind waves and wind stress fields from voluntary observing ship data. *J. Phys. Oceanogr.*, **28**(6), 1107–1130 (doi: 10.1175/1520-0485(1998)028<1107:NAWWAW>2.0.CO;2)

Gulev SK and Hasse L (1999) Changes of wind waves in the North Atlantic over the last 30 years. *Int. J. Climatol.*, **19**(10), 1091–1117 (doi: 10.1002/(SICI)1097-0088(199908)19:10<1091::AID-JOC403>3.0.CO;2-U)

Jevrejeva S and Leppäranta M (2002) Ice conditions along the Estonian coast in a statistical view. *Nord. Hydrol.*, **33**(2–3), 241–262 (doi: 10.2166/nh.2002.014)

Kahma K, Pettersson H and Tuomi L (2003) Scatter diagram wave statistics from the northern Baltic Sea. *MERI: Rep. Ser. Finn. Inst. Mar. Res.*, **49**, 15–32

Kartau K, Soomere T and Tõnisson H (2011) Quantification of sediment loss from semi-sheltered beaches: a case study of Valgerand Beach, Pärnu Bay, the Baltic Sea. *J. Coastal Res.*, **SI 64**, 100–104

Komen GJ, Cavaleri L, Donelan M, Hasselmann K, Hasselmann S and Janssen PAEM (1994) *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambridge

Leppäranta M (1981) *On the structure and mechanics of pack ice in the Bothnian Bay*. (Finnish Marine Research 248) Finnish Institute of Marine Research, Helsinki

Leppäranta M (2013) Land–ice interaction in the Baltic Sea. *Estonian J. Earth Sci.*, **62**(1), 2–14 (doi: 10.3176/earth.2013.01)

Leppäranta M and Myrberg K (2009) *Physical oceanography of the Baltic Sea*. Springer Praxis, Berlin

Mietus M (1998) *The climate of the Baltic Sea basin: the final report of WMO project*. (Marine Meteorology and Related Oceanographic Activities Report 41) World Meteorological Organisation, Geneva

Myrberg K and 19 others (2010) Validation of three-dimensional hydrodynamic models of the Gulf of Finland. *Boreal Environ. Res.*, **15**(5), 453–479

Orviku K, Jaagus J, Kont A, Ratas U and Rivis R (2003) Increasing activity of coastal processes associated with climate change in Estonia. *J. Coastal Res.*, **19**(2), 364–375

Overeem I, Anderson RS, Wobus CW, Clow GD, Urban FE and Matell N (2011) Sea ice loss enhances wave action at the Arctic coast. *Geophys. Res. Lett.*, **38**(17), L17503 (doi: 10.1029/2011GL048681)

Räämet A and Soomere T (2010) The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian J. Earth Sci.*, **59**(1), 100–113 (doi: 10.3176/earth.2010.1.08)

Räämet A, Suursaar Ü, Kullas T and Soomere T (2009) Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *J. Coastal Res.*, **SI 56**, 257–261

Ryabchuk D, Kolesov A, Chubarenko B, Spiridonov M, Kurennoy D and Soomere T (2011) Coastal erosion processes in the eastern Gulf of Finland and their links with geological and hydrometeorological factors. *Boreal Environ. Res.*, **16**(Suppl. A), 117–137

Schmager G, Fröhle P, Schrader D, Weisse R and Müller-Navarra S (2008) Sea state, tides. In Feistel R, Nausch G and Wasmund N eds. *State and evolution of the Baltic Sea, 1952–2005: a detailed 50-year survey of meteorology and climate, physics, chemistry, biology, and marine environment*. Wiley, Hoboken, NJ, 143–198

Sooäär J and Jaagus J (2007) Long-term changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proc. Estonian Acad. Sci. Eng.*, **13**(3), 189–200

Soomere T (2008) Extremes and decadal variations of the northern Baltic Sea wave conditions. In Pelinovsky E and Kharif C eds. *Extreme ocean waves*. Springer, Berlin, 139–157

Soomere T and Keevallik S (2001) Anisotropy of the moderate and strong winds in the Baltic Proper. *Proc. Estonian Acad. Sci. Eng.*, **8**(1), 35–49

Soomere T and Keevallik S (2003) Directional and extreme wind properties in the Gulf of Finland. *Proc. Estonian Acad. Sci. Eng.*, **9**(2), 73–90

Soomere T and Räämet A (2011) Spatial patterns of the wave climate in the Baltic Proper and the Gulf of Finland. *Oceanologia*, **53**(1-TI), 335–371

Soomere T and Zaitseva I (2007) Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proc. Estonian Acad. Sci. Eng.*, **13**(1), 48–64

Soomere T, Zaitseva-Pärnaste I and Räämet A (2011) Variations in wave conditions in Estonian coastal waters from weekly to decadal scales. *Boreal Environ. Res.*, **16**(Suppl. A), 175–190

St-Hilaire-Gravel D, Forbes DL and Bell T (2012) Multitemporal analysis of a gravel-dominated coastline in the central Canadian Arctic Archipelago. *J. Coastal Res.*, **28**(2), 421–441 (doi: 10.2112/JCOASTRES-D-11-00020.1)

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

Tuomi L, Kahma KK and Pettersson H (2011) Wave hindcast statistics in the seasonally ice-covered Baltic Sea. *Boreal Environ. Res.*, **16**(6), 451–472

US Army Corps of Engineers (USACE) (2002) *Coastal engineering manual.* (USACE Report No. EM 1110-2-1100) US Army Corps of Engineers, Washington, DC

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