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Spatio-Temporal Variability of the Baltic Sea Wave Fields

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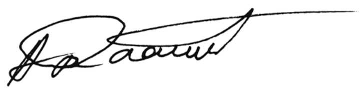
Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree.



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TTÜ KIRJASTUS

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Glossary

Bathymetry. The description of water depths in oceans, seas and lakes. Bathymetric charts usually show seafloor relief by contour lines called isobaths.

Diurnal. A cycle that recurs after each 24 hours.

Fetch. The area over which waves are generated by the wind.

Fetch length. The horizontal distance in the direction of the wind over which wind waves are generated.

Frequency of the wave. The number of waves that pass a fixed point in a given time. The unit of frequency is Hertz, which means waves per second.

Fully developed sea. The sea state that forms under suitable conditions when the wind blows for a sufficient time over the open sea. The waves reach their maximum possible height for a given wind speed, fetch length and duration of the wind.

Geostrophic wind. The wind which results from the balance between the Coriolis force and the pressure gradient force above the friction layer. Blows parallel to air pressure isobars.

Offshore. The direction seawards from the shore.

Shoaling. The effect of the bottom on waves propagating into shallow water where the waves begin to slow down and the wave heights start to increase.

Significant wave height. The average height of the one-third highest waves, more recently, the fourfold standard deviation of the sea surface elevation.

Swell. Wind-generated waves that have travelled long distances away from their generating area and are not any more affected by the wind.

Topography. The description of surface shapes and features.

Wave breaking. The wave energy dissipation process in shallow areas due to limited water depth where the upper part of the wave becomes faster than the lower part and starts to overtake it.

Wave hindcast. Reproduction of past wave climate by numerical modelling using measured or modelled wind information.

Wave period. The time it takes for two successive wave crests to pass a fixed point.

Wave spectrum. Mathematical description of the distribution of wave energy as a function of wave frequency and/or propagation direction.

Whitecapping. The wave energy dissipation process under deep-water conditions. When the wave is growing, it becomes steeper. After reaching a critical point the wave breaks. This process limits wave growth in open seas.

Windseas. The wind wave system which is directly generated and affected by the recent local winds (cf. swell).

Wind waves. Waves which are formed and built up by the local wind.

Introduction

Surface waves in the changing world

A substantial part of the energy and momentum submitted to the water masses by winds blowing over the sea surface is carried further in the form of surface waves. As the sea surface is an almost perfect waveguide for propagating wave energy, wind waves and swell may travel over thousands of kilometres and meet other wave systems of similar kind. A clear perception of the properties of typical and extreme waves and their potential changes in variable climate conditions is the starting point of reliable design of ships and offshore structures.

Further on, systems of waves with various properties bring to the coastline massive amounts of energy. The large damaging potential of high storm waves motivates the analysis of surface waves and their possible impact on the coasts as an intrinsic component of marine-induced hazards to the coastal zone. The flow of wave energy towards the coasts is responsible for a great many processes in the nearshore, ranging from long-term accumulation, erosion and degradation that gradually shape the coasts to various marine-induced hazards and disasters. A comprehensive understanding of the properties of the approaching waves is the key precondition for the design and operation of virtually all coastal engineering structures and the major knowledge necessary for mitigation of various marine hazards and for sustainable management of the coastal region. Moreover, the wave climate is one of the most sensitive indicators of changes in the wind regime and local climate in semi-enclosed sea areas (Weisse and von Storch, 2010).

The Baltic Sea is a unique water body, the dynamics of which involves features of a large lake, large estuary and a small ocean (BACC, 2008). The combination of its relatively small size, the vulnerability of its ecosystem and comparatively young coasts makes this region extremely susceptible both to climate changes and anthropogenic pressure (Leppäranta and Myrberg, 2009).

The anisotropic nature of the Baltic Sea wind and wave fields (Soomere, 2003; Jönsson et al., 2002, 2005) suggests that the eastern coast of the Baltic Sea, and especially the nearshore and the coast of western and north-western Estonia, are probably under the largest natural pressure among the variety of the coasts of this water body. These coasts are to a large extent in active evolution and the potential changes in the forcing are expected to become evident relatively fast (Orviku et al., 2003). The coastal areas host several major cities and ports, part of which are still under intensive development. The potential increase in the frequency and/or severity of marine coastal hazards may substantially affect the planning, operation, maintenance and reconstructions of the relevant infrastructure.

Measurement of ocean waves is one of the most complicated problems in oceanography not only because of the complexity of wave-related phenomena but also because of enormous forces that may become evident in the field of high waves. This is one of the reasons why there are very few wave measurement sites in the open sea. For example, regular instrumental wave measurements near the coasts of the northern Baltic Proper only started at the end of the 1970s (Broman et al., 2006) and contemporary wave measurement devices were deployed in the open sea in the mid-1990s, whereas, for example, water level measurements have been carried out at several sites around this water body for more than 100 years.

Given the limited amount of measured or observed wind wave data, numerical simulations play an increasing role in estimates of the basic features of open sea wave climate (and its changes) and in the understanding of the typical and extreme wave properties in selected coastal sections. Such simulations are especially important for understanding the potential changes in the wave regime. Namely, these changes are usually much more extensive than changes in wind properties. A simple reason behind this feature is that the wave height is frequently proportional to the wind speed squared. Also, even small changes in the wind direction in elongated sea areas may lead do drastic changes in wave heights, periods and propagation directions because of changes in the effective fetch length.

The listed issues, although important in the open ocean conditions, are essential in the Baltic Sea as well. Here numerous changes in the forcing conditions followed by the reaction of water masses, have been reported during the last decade. A number of such observations, especially changes in the evolution of the coasts, can be related to alterations in typical or extreme wave conditions. There is even evidence that these changes have already caused extensive erosion of several depositional coasts (Orviku et al., 2003; Ryabchuk et al., 2009, 2010). This conjecture may partly arise from quite a subtle feature, namely, a drastic increase in the frequency of south-western winds over the latter half-century (Kull, 2005; Jaagus, 2009), which may result in a combination of an increase in wave periods and a change in the wave propagation direction. This opinion is tightly related to a considerable increase in the probability of occurrence of high water levels within the last half-century (Johansson et al., 2001).

There is, however, highly controversial evidence about the reaction of some properties of wave fields to changes in the forcing conditions. For example, wave heights apparently increased in the northern Baltic Proper in the 1970s and the 1980s until the middle of the 1990s at Vilsandi (according to visual observations, Soomere and Zaitseva, 2007) and Almagrundet (where wave properties were measured with the use of an upward-directed echo sounder; Broman et al., 2006). A rapid decrease in the annual mean wave heights started in this area in the mid-1990s (Broman et al., 2006; Soomere and Zaitseva, 2007).

Although contemporary efforts towards clarifying such issues in large scales by using numerically reconstructed global wave data sets such as KNMI/ERA-40 Wave Atlas (09.1957–08.2002, Sterl and Caires, 2005) allow detection of the basic features of wave climate and their changes in the open ocean conditions, the spatial resolution (1.5°×1.5°) of such databases is too sparse for an adequate representation of the Baltic Sea conditions. One of the few feasible ways to fill this gap consists in systematic high-resolution numerical simulations of the Baltic Sea wave climate which form the key task of this thesis.

The Baltic Sea – a challenge for surface wave research

The Baltic Sea (Figure 1) is a challenging area for wave scientists. In winter, frequent stormy winds and the presence of heavy ice often complicate both visual observations and instrumental measurements. As floating devices are usually removed well before the ice season (Kahma et al., 2003), the overall wave statistics do not contain data from the windiest period that frequently occurs just before the ice cover is formed. Extensive relatively shallow areas in this basin may host extremely complex wave fields and unexpectedly high waves, formed in the process of wave refraction and optional wave energy concentration in some areas (Soomere, 2003, 2005; Soomere et al., 2008).

Although storm waves in this water body are relatively steep and short, and thus comparatively dangerous for smaller craft, it has been believed that the small size of the sea together with rare occurrence of favourable conditions for generation of high waves effectively limit the wave heights and periods. On the one hand, this belief has been confirmed by estimates of wave energy (e.g. Bernhoff et al., 2006). The existing measurements of wave properties in the north-eastern part of the basin (where the wave heights are expected to be the largest) (Kahma et al., 2003) suggest that the significant wave heights hardly exceed 8–8.5 m and that wave conditions with $H_S > 7$ m (which have occurred <10 times since 1978, Soomere, 2008) can be interpreted as extreme situations.

On the other hand, consequences of wave events have been most serious and at times catastrophic in the Baltic Sea. The most devastating accident was the loss of the passenger ferry *Estonia* in autumn 1994, which took 852 lives, owing to wave damage (Karppinen and Ling, 1998).

The available data suggest that the changes in the Baltic Sea wave climate have been marginal from the late 1950s until the early 1990s (Broman et al., 2006; Soomere and Zaitseva, 2007). Together with the above-discussed increase in wave activity from the 1980s, this temporal course basically matches the recent findings about the storminess in the Baltic Sea region that was relatively high at the beginning of the 20th century, decreased in the middle of this century and increased to the original level in the 1980s–1990s (Alexandersson et al., 2000).

The evidence of temporal changes in wave properties is contradicting as well. For example, wave heights along the Lithuanian coast show no substantial changes over the 1990s and after the turn of the millennium (Kelpšaite et al., 2008). The most interesting feature is the mismatch of the decadal variability in wave heights and wind speed over the northern Baltic Proper: while the wave activity reveals rapid decadal-scale variations at both eastern and western coasts of the northern Baltic Proper, the annual mean wind speed at the Island of Utö only shows a gradual increase over this time (Broman et al., 2006). Therefore, long-term variability of wave fields in the northern Baltic Proper seems to be weakly correlated with the variations in the average wind speed. This mismatch has led to the question about the reliability and drivers of the established wave climate changes, which is one of the key questions addressed in this thesis.

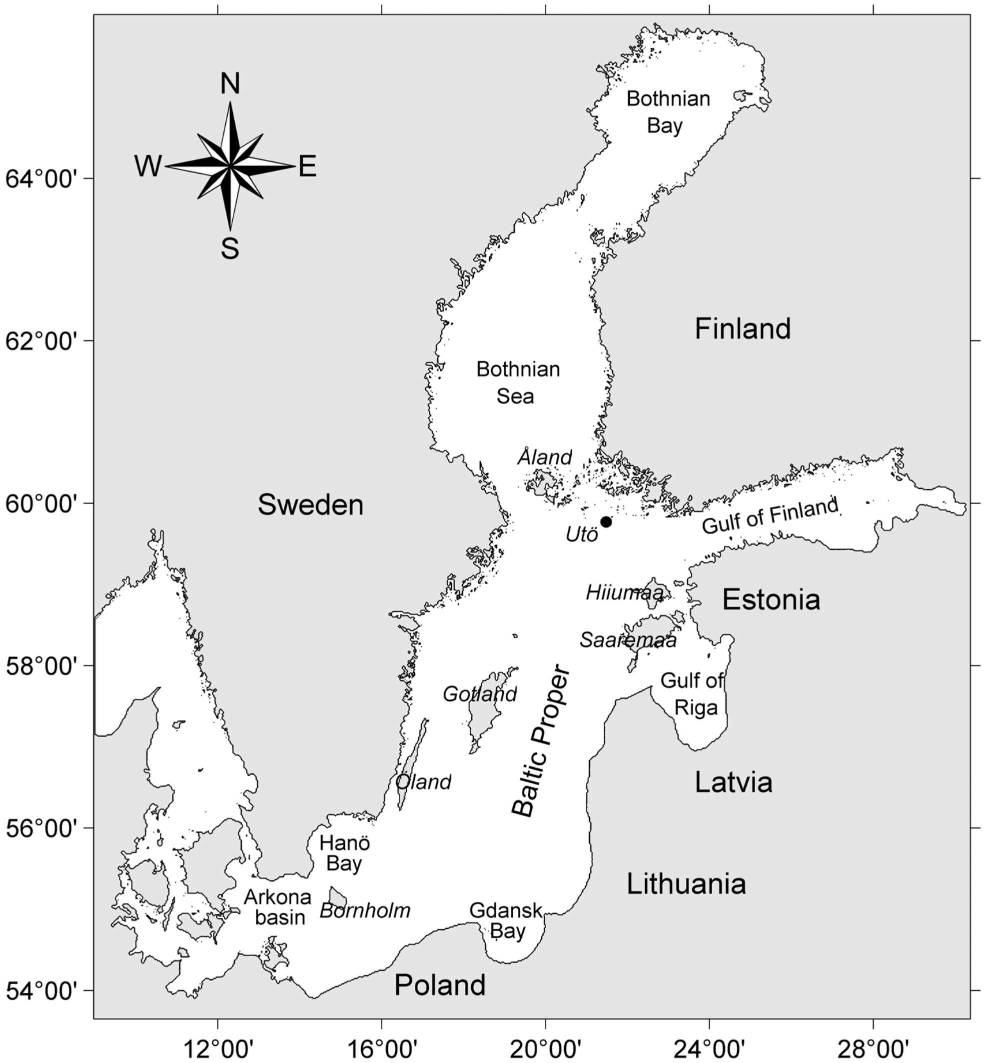

Figure 1. Location scheme of the Baltic Sea

An important feature of wave conditions since the mid-1990s has been the seeming increase in the number of extreme wave conditions on the background of the overall decrease in mean wave heights in the northern Baltic Sea. Several cases of hazardous wave conditions occurred at the turn of the millennium – in December 1999 in the Baltic Proper (Kahma et al., 2003) and in November 2001 in the Gulf of Finland (Soomere, 2005). Ferocious winter storms of 2004/2005 created extremely rough seas in the entire Baltic Sea (Suursaar et al., 2006) and the legendary storm Gudrun probably caused the all-time highest significant wave height (Soomere et al., 2008). In particular, these storms have extensively affected the depositional shores of the eastern Baltic Proper (Eberhards et al., 2006; Tõnisson et al., 2008).

This circumstance has led to the following questions: (i) Have the coastal processes in the Baltic Sea become more intense when compared to the situation a few decades ago or not? (ii) Are the trends for average and extreme wave heights different? (iii) Are the trends in wave properties similar for the North Atlantic and for different regions of the Baltic Sea or not?

There is some uncertainty about the significance of various factors (such as instrument failure, observer's error or noise in the data; Broman et al., 2006; Soomere and Zaitseva, 2007) affecting the observed and measured changes. As the above-described changes occurred simultaneously, and with a similar relative range at both eastern and western coasts of the northern Baltic Proper in the 1990s, it is not very likely that they were entirely caused by failures of instruments or the relay of the observers. More likely they expose certain large-scale decadal variations in the wave properties in certain sea areas. Visually observed wave data from the Island of Vilsandi, however, suggest that these changes were not necessarily reflected in wave activity (Soomere and Zaitseva, 2007).

As these changes have straightforward implications on the potential intensification of beach processes, there exists an obvious necessity for re-evaluation of the basic features of temporal variability of wave properties along the coasts of the northern Baltic Proper. An additional relevant issue lies in the clarification of whether the mismatches between different wave data sets stem from the uncertainties of wave models and measurements, represent properties of local wave fields or form a part of long-term changes. The set of wave data is fairly small in this area and evidently does not reproduce spatial variability of the wave fields.

The information is particularly fragmentary for the eastern part of the Baltic Proper and especially for the Gulf of Finland (Soomere et al., 2008) and Estonian coastal waters. This area is characterized by extremely complex geometry and large variations in wave propagation conditions (Soomere, 2005; Laanearu et al., 2007), and contemporary instrumental wave measurements are almost missing here.

There are several ways for obtaining estimates of local wave climate. Usually wave statistics are either modelled numerically or extracted from long-term wave measurements. The use of wave observations has always been problematic because of the lack of reliable data from the open sea areas. This is caused not only by the high cost and difficulty in organizing field experiments. Coarse measurements of wave properties at a few sites along a highly variable coastline frequently do not contain sufficient information about spatial variability of wave fields. Owing to the extremely complex geometry and bathymetry of the Baltic Sea, it is often almost impossible to reconstruct the properties of the local, nearshore wave regime or its changes from a few available wave data sets.

The most promising method for establishing the properties of the local wave climate is wave modelling. An adequate reproduction of wave properties is a major challenge in this area and can hardly be realized on the basis of simple (for example, fetch-based) models using standard one-point wind information (which are, though, adequate for semi-sheltered sea areas with a short memory of wave fields; Soomere, 2005).

Several attempts to reconstruct the wave climate numerically have been undertaken for many areas of the Baltic Sea (e.g. Paplinska, 1999, 2001; Blomgren et al., 2001; Cieslikiewicz and Herman, 2002; Soomere, 2003, 2005, 2008; Cieślikiewicz and Paplińska-Swerpel, 2008; Kriezi and Broman, 2008). Most of the reconstructions, however, cover relatively short periods of a few years or concentrate on specific areas of the Baltic Sea. Long-term reconstructions of wave fields over the entire Baltic Sea are still a complicated task for scientists and usually contain extensive uncertainties (Cieslikiewicz and Paplinska-Swerpel, 2008; Kriezi and Broman, 2008).

The most important source of the uncertainties in the hindcasts of wave fields is the low quality of the historical wind information. Typically, for larger sea areas such as the Baltic Proper, geostrophic winds or the derivatives from local atmospheric models such as the MESAN (operational Mesoscale Analysis System) database (developed at the Swedish Meteorological and Hydrological Institute (SMHI) to produce hourly gridded wind information on a 22 km grid since October 1996; Häggmark et al., 2000) are commonly used as substitutes of the true wind fields. The reliability of wave field reconstructions for the open Baltic Sea based on this wind information is still quite low, even if the most up-to-date wave models are used (Räämet et al., 2009).

In short, there exists no reliable assessment of the spatio-temporal variability of the wind-wave intensity for the Baltic Sea in the international scientific literature.

The main objective of this thesis is to adequately estimate the wind wave climatology for the Baltic Proper and the Gulf of Finland, with a focus on the coastal waters of Estonia, by using the high-resolution contemporary spectral wave model and high-quality wind fields. This is evidently the only way to properly account for the complexity of geometry and bathymetry of the Baltic Sea and extensive variations in the wind properties over the Baltic Sea. As will be demonstrated below, this method makes it possible to obtain reliable wave statistics and to identify both temporal and spatial patterns of variations in the basic properties of the wave field.

There remain, however, quite large uncertainties in estimates of wave properties in extreme storms stemming from imperfections of even the best available wind fields. Also, in this study, ice conditions are generally not accounted for. Sea ice is an important factor influencing wave fields in the Baltic Sea: it not only reshapes the area of wave generation (fetch length, thereby affecting waves even far downwind from the ice region) but also affects atmospheric conditions so that the wind speed over a frozen sea may be larger than over rough wind-generated seas. The focus below is on detecting the climatological changes in wave properties that are driven directly by changes in the wind conditions.

In order to obtain maximally reliable estimates of the wave climate, a combination of different data sources with extensive modelling resources is used.

In particular, an attempt is made to merge historical visual observations and numerical hindcast to reveal the seasonal, annual and decadal changes in the basic wave properties in different parts of the Baltic Proper and Estonian coastal waters.

The particular objectives of the thesis are as follows:

- to create reliable climatological wind wave statistics for the Baltic Proper, for the Gulf of Finland and for Estonian coastal waters;
- to evaluate the basic features of long-term changes in the wave properties in the northern Baltic Proper;
- to identify potential spatial patterns of variations in basic wave parameters, especially in wave height;
- to clarify whether the wave model and wind data in use are able to identify drastic changes in the wave climate.

Outline of the thesis

In the first chapter I give an insight into wave climate studies in the North Atlantic, the North Sea and the Baltic Sea. The North Atlantic is generally believed to host the roughest wave conditions in the World Ocean (Grigorieva and Gulev, 2006). As the majority of storms creating substantial wave heights in the Baltic Sea are born in the North Atlantic, potential changes in the wave conditions in this area evidently sooner or later will result in certain changes also in the Baltic Sea wave climate.

The North Sea basin is to some extent separated from the processes in the entire North Atlantic. It is, however, located in the immediate neighbourhood of the southern Baltic Sea and thus the changes in the factors driving the local North Sea wave properties should become simultaneously evident in the southern Baltic Sea basin. The existing data for the Baltic Sea are mostly described from the viewpoint of the northern Baltic Proper and the Estonian coastal waters. Here I make an attempt to merge historical visual observations and numerical hindcast to highlight the known features of the seasonal, annual and decadal changes in the basic wave properties.

Chapter 2 first gives a short overview of the state-of-the-art of wave modelling and applications of contemporary wave modelling techniques in the Baltic Sea conditions. The specific requirements for successful reproduction of the wave fields in this basin are discussed in detail. For example, in order to ensure adequate wave growth rates after calm conditions, the model has to account for very short waves, with periods up to 2 Hz. The suitability of different wind data sets for the purpose of this study is analysed and, finally, several quantitative measures of the model performance are described.

The basic features of the wave climate in the northern Baltic Proper and along the North Estonian coast are presented in Chapter 3. I perform a detailed comparison of the key statistical features of the wave regime obtained by means of numerical modelling, instrumental wave measurements and visual observations from coastal hydrometeorological stations. Further on, I present an overview of the seasonal cycle in wave properties in Estonian coastal waters and compare it with similar changes in wind properties.

The evidence about long-term changes in various wave properties and discussion of their potential consequences from the viewpoint of coastal processes and coastal engineering are presented in Chapter 4. The central characteristic here is the significant wave height, long-term changes in which reveal very complicated spatio-temporal patterns. While almost no identifiable changes occur in wave periods, changes in wave heights in extreme storms also show several nontrivial patterns. The performed experiments, however, leave still open the question about reliability of the changes in wave directions identified from visual observations.

Approbation of the results

The basic results described in this thesis have been presented in the following international conferences:

1. **Räämet, A**., 2008. On the variability of the Baltic Sea wave fields. Poster presentation at the 3rd International student conference *"Biodiversity and functioning of Aquatic Ecosystems in the Baltic Sea Region"*, 9–12 October 2008, Klaipeda, Lithuania.
2. **Räämet, A**., Suursaar, Ü., Kullas, T. and Soomere, T., 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. Oral presentation at the 10th International Coastal Symposium, 13–18 April 2009, Lisbon, Portugal.
3. **Räämet, A**., 2009. Simulating long-term changes of wave conditions in the northern Baltic Sea. Oral presentation at the 7th Baltic Sea Science Congress, 17–21 August 2009, Tallinn, Estonia.
4. **Räämet, A**. and Soomere, T., 2009. Wave climate changes in the Baltic Proper 1978–2007. Oral presentation at the 4th International student conference *"Biodiversity and functioning of Aquatic Ecosystems in the Baltic Sea Region",* 2–4 October 2009, Dubingiai, Lithuania.
5. **Räämet, A**. and Soomere, T., 2010. A reliability study of wave climate modelling in the Baltic Sea. Oral presentation at the 6th Study Conference on BALTEX, 14–18 June 2010, Międzyzdroje, Island of Wolin, Poland.
6. Zaitseva-Pärnaste, I., **Räämet, A**. and 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 (accepted).

The thesis is based on four academic publications which are referred to in the text as Paper I, Paper II, Paper III and Paper IV. Papers I–III are indexed by the ISI Web of Science and Paper IV is under review in a journal indexed in this database:

Paper I **Räämet, A**., Suursaar, Ü., Kullas, T. and Soomere, T., 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *Journal of Coastal Research,* Special Issue 56, Part I, 257–261.

Paper II **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.

Paper III **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.

Paper IV Soomere, T., Zaitseva-Pärnaste, I. and **Räämet, A**., 2010. Seasonal and long-term variations in wave conditions in Estonian coastal waters. *Boreal Environment Research* (submitted).

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And finally, I would like to thank my family for encouraging and supporting me throughout my studies.

1. Wave climate studies in the North Atlantic region and the Baltic Sea

Wave conditions in the Baltic Sea basin, albeit formally independent of properties of windseas and swells occurring in the World Ocean, are still largely defined by the same atmospheric conditions that govern wave fields in the North Atlantic and in the North Sea. Most of the air pressure systems steering wave fields in the Baltic Sea stem from the North Atlantic. Therefore, wave conditions in the Baltic Sea basin, especially their long-term changes and spatial variability are largely governed by changes in the cyclonic intensity in the North Atlantic and by the propagation trajectories of air pressure systems to the east. In this light, a large part of changes in the wave properties in the Baltic Sea are directly connected with similar changes in wave fields in the North Atlantic and North Sea.

The North Atlantic region has been the target area of most of the pioneering studies into global wave fields and attempts at numerical reconstruction of wave properties in large scales. For example, the concept of the saturated wave systems (with the so-called Pierson–Moskowitz spectrum) is based on a large pool of observations of wave conditions in long-lasting storms in this region. The seminal JONSWAP (Joint North Sea Wave Project) experiment (which led to the establishing of the contemporary understanding of the wave growth under areas with limited fetch) has been performed in the North Sea in the nearshore of the Island of Sylt (Komen et al., 1994).

These aspects motivated the necessity of an overview of the existing knowledge of the basic features of wave climate, its changes and numerical reconstructions based on the relevant research in the North Atlantic (Section 1.1) and in the North Sea (Section 1.2). Further on, a selection of the existing data for the Baltic Sea basin is described in detail from the viewpoint of the northern Baltic Proper and especially the Estonian coastal waters. In the light of the attempt to merge historical visual observations and numerical hindcast to highlight the known features of the seasonal, annual and decadal changes in the basic wave properties, I describe the results of the instrumental wave measurements in the northern Baltic Proper (Section 1.3), give an overview of visual wave observations along the eastern coast of the Baltic Sea (Section 1.4) and depict the key outcome of wave climate studies for the northern Baltic Sea (Section 1.5). The material is presented in greater detail than in the relevant sections of Papers I–IV.

1.1. North Atlantic

The North Atlantic region probably hosts the world's roughest wave climate (Grigorieva and Gulev, 2006) over the Northern Hemisphere oceans. Although formally estimated on the basis of observation data from voluntary observing ships in terms of the highest 100-year return value, this property of the North Atlantic is generally recognized by wave scientists (Caires and Sterl, 2005a). High waves are created in this region by the interplay of the frequent generation of strong cyclones and steering of their motion and the resulting wind fields by the presence of high orography in Greenland, Island and Scandinavia. Holliday et al. (2006) claim that the highest ever instrumentally measured significant wave height $H_S = 18.5$ m has been registered at Rockall, west of Scotland. The second highest significant wave height, 17.9 m, has been measured in the Gulf of Mexico (Wang et al., 2005). The highest recorded single wave with a height of 32.3 m, however, has been filed under typhoon Krosa in the Pacific (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 this region. Earlier studies into these issues have led to controversial results. For example, an increasing trend in mean wave heights throughout the whole of the North Atlantic, possibly since 1950 and on average by about 2% per year, was found by Bacon and Carter (1991). The scarcity of data made it impossible to identify whether the mean properties or extreme values of the wave climate are increasing.

The international WASA (Waves and Storms in the North Atlantic) project was set up in the middle of the 1990s to verify or refute hypotheses of a worsening storm and wave climate in the north-east Atlantic and its adjacent seas during the 20th century (WASA Group, 1998). The analysis concluded that wave climate in the north-east Atlantic and in the North Sea has undergone significant decadal variations (partially related to the North Atlantic Oscillation) but revealed no clear trends. Although there was a certain tendency towards rougher seas during recent decades, the wave intensity at the end of the 1990s seemed to be comparable with that at the beginning of the 20th century.

Wave climate studies based on data from voluntary observing ships

A substantial contribution towards quantification of the basic wave properties and their potential changes was achieved at the end of the 1990s when Gulev and Hasse (1998) evaluated major parameters of the sea state for the North Atlantic on the basis of the extensive collection of wave conditions, which was recorded visually by a voluntary observing ship (VOS) and is available from the Comprehensive Ocean–Atmosphere Data Set (COADS). This data set enabled adequate estimation of climatological parameters of both wind waves and swell in terms of the height and period of both the counterparts of the sea state as well as the resultant significant wave height and period for the years 1964–1993. This time interval (30 years) is usually thought to be long enough for proper identification of changes in the relevant climatological parameters. Validation of the results against instrumental records from the National Data Buoy Center buoys and ocean weather station measurements indicated relatively good agreement for wave heights and certain systematic biases in the visually estimated periods (that were corrected afterwards).

Long-term changes in wind wave heights, derived from visual estimates available from the COADS for the period 1964–1993, were discussed by Gulev and Hasse (1999). The authors successfully demonstrated that observations from merchant ships can be effectively used for the study of changes in wave climate and storminess. The significant wave height was shown to increase by 10–30 cm per decade over the entire North Atlantic, except for the western and central subtropics (Gulev and Hasse, 1999). These changes were found to result primarily from the increase in the intensity of swell and thus to reflect to certain extent a systematic dislocation of the major storms, potentially to a more southern position, over the analysed time interval. The properties of local windseas revealed great changes in the central mid-latitudinal North Atlantic but did not show any significant variation in the north-eastern Atlantic (where instrumental records of Bacon and Carter (1991) reported secular changes).

In the context of the potential use of visual observations from the coasts of the eastern Baltic Sea for identification of long-term changes in wave properties, it is important to notice that the alterations in significant wave height observed from ships have generally been found to be quite consistent with those shown by the instrumental records.

The development and validation of a global climatology of main wave parameters on the basis of data from the COADS collection are introduced by Gulev et al. (2003). The climatology covers the years 1958–1997 and presents wave heights and periods for the windseas, swell and significant wave height over the global ocean on a resolution of 2°×2°. They applied special algorithms of corrections to minimize some biases, inherent in visual wave data. Biases associated with inadequate sampling density were quantified using the data from a high-resolution WAM (Wave Model; Komen et al., 1994) hindcast for the period 1979–1993. I used a similar approach in comparisons of the observed and modelled long-term changes in wave fields in Paper IV. The highest sampling biases were observed in the South Ocean, where wave height may be underestimated by 1–1.5 m.

Secular changes and interannual variability in the windseas, swell and significant wave height over the North Atlantic and North Pacific for the years 1958–2002 were analysed by Gulev and Grigorieva (2006) using a similar data set of visual wave observations from voluntary observing ships. In both North Atlantic and North Pacific mid-latitudes, the winter significant wave height was found to show a secular increase of about 10–40 cm per decade. For the North Atlantic the patterns of changes in the properties of windseas and swell were quite different and showed even opposite signs for the north-eastern Atlantic. The most interesting result from the viewpoint of the Baltic Sea wave fields (where the role of swell is quite small (Broman et al., 2006)) is the overall increase in the windseas wave height during the winter season over the time period in question on the background of almost unchanged annual mean wave properties.

NCEP/NCAR reanalysis

The first global wave data set based on the numerical reanalysis of wave properties using realistic wind fields and contemporary spectral wave models was compiled in the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis project that was developed to produce a record of global analyses of atmospheric fields. This project involves the recovery of land surface, ship, rawinsonde, pibal, aircraft, satellite and other data, which were quality controlled and assimilated with an assimilation system that was kept unchanged over the entire 40-year reanalysis period from 1957 to 1996 (Kalnay et al., 1996).

Three alternative marine surface-level wind fields from the NCEP/NCAR reanalysis were compared by Cox et al. (1998) in order to hindcast the surface wave field in the North Atlantic. The errors in the wind fields were assessed through evaluation of the resulting wave hindcasts against wave measurements. The comparison was performed during eight months over the period from 1979 to 1995. The NCEP surface (10 m level) winds were found to produce the least biased and overall most skilful wave hindcast.

The resulting marine surface wind fields produced in the NCEP/NCAR reanalysis project were used to drive the third-generation wave model OWI 3-G (Swail and Cox, 2000). In general, these winds were shown to produce wave hindcasts of good quality, which were relatively unbiased and with a low scatter index compared to buoys and satellite data.

A wind and wave hindcast for the North Atlantic for the 40-year period from 1958 to 1997 using a long-term consistent wind forcing based on the NCEP reanalysis and spectral wave model OWI 3-G was presented by Swail et al. (1998). Further on, Swail et al. (2000) performed the validation of this (called AES40) hindcast wind and wave fields, and an analysis of the wave climate, its trends and variability. Somewhat differently from the above data, they detected a significant increasing trend in wind speeds and wave heights in the north-eastern Atlantic and a decreasing trend in the central North Atlantic.

A newly developed, high-resolution and quality controlled surface meteorology data set from research vessels for the period 1990–1995 were used by Smith et al. (2001) to quantify regional and global uncertainties for the NCEP/NCAR reanalysis products. The primary results showed a significant underestimation of the near-surface wind speed in NCEP/NCAR reanalysis.

Although slightly out of the scope of this thesis, it is still interesting to mention that the revised NCEP/NCAR reanalysis data set and *in situ* data were compared against each other in order to show changes in the winter cyclone activity of the North Pacific during the past 50 years (Graham and Diaz, 2001). The key result was a significant increase in both the frequency and intensity of extreme cyclones. The accompanying wave hindcast showed that the wave climate over the North Pacific has become much rougher since the 1950s, with extreme wave heights increasing on the order of 1–2 m (by about 20–30% of the long-term mean).

A similar significant intensifying trend of cyclonic activity in winter during the past 40 years (1958–1998) was also reported using reanalysed wind to study cyclonic activity over the North Atlantic (Geng and Sugi, 2001). Further on, Wang and Swail (2001) identified trends in seasonal 90%-iles and 99%-iles of significant wave height for the North Atlantic and for the North Pacific using 40-year (1958–1997) numerical hindcast. They determined statistically significant changes in the seasonal extremes of significant wave height in the North Atlantic for the winter (January–March) season. An increase in the significant wave height in the north-east North Atlantic was accompanied by its decrease in the subtropical North Atlantic. This feature was associated with an intensified Azores high and a deepened Icelandic low. The use of kinematically reanalysed wind fields for detailed study in the North Atlantic allowed of the conclusion that the wave hindcast shows a more significant increase in the region off the Canadian coast in summer and autumn, and a higher increase in the region north-west of Ireland in winter (Wang and Swail, 2002).

An analysis of the storm climate of the north-east Atlantic for the period 1958–2001 was presented by Weisse et al. (2005). The regional climate model was driven by the NCEP weather reanalysis. They concluded that the average number of storms had increased near the exit of the North Atlantic storm track during this period, but the average number of storms per year was decreasing over the north-east Atlantic from about 1990–1995. The frequency of the most severe storms followed a similar pattern.

ECMWF reanalysis

A statistical hindcast of the wave properties over the period since 1960 was made by Kushnir et al. (1997) using the winds calculated by the European Centre for Medium-Range Weather Forecasts (ECMWF). This study revealed an increase in significant wave height at several locations in the North Atlantic. This increasing trend was shown to be related to the systematic deepening of the Icelandic low and intensification of the Azores high.

The subsequent major developments in numerical quantification of wave climate and its changes were the so-called ERA-15 and ERA-40 reanalysis projects with the former covering a multitude of hydrometeorological data over 15 years (December 1979 – February 1994) and the latter over 45 years 1957–2002. This mission was accomplished by the ECMWF to produce data describing the state of the atmosphere four times a day. A thorough description of this task, a summary of the general aspects of the production of the analyses, including the data acquisition, changes in data type and coverage over the period and also the data assimilation system, is given by Uppala et al. (2005).

The surface winds from the ERA-15 project were used by Sterl et al. (1998) to drive a WAM model to assess the quality of the ERA winds and to describe changes in wave heights over the period from 1979 to 1993. The patterns of modelled wave heights were found to agree well with the observed patterns. The hindcast data were analysed in terms of the annual cycle and trends. The key conclusion of the analysis was, in some sense, negative, as no significant change in wave heights during the ERA period was identified. In the light of later research, this conjecture is not unexpected because the typical time scale of changes in wave parameters is from 15 to 30 years (Vikebø et al., 2003; Soomere, 2008).

From comparisons between different data sets it was concluded that in most cases the ERA-40 reanalysis provided better results than the ERA-15 and NCEP/NCAR reanalysis. The ERA-40 data also contain information about waves in the form of the Web-based KNMI/ERA-40 wave atlas with a spatial resolution of 1.5°×1.5° based on 6-hourly means of wave properties (Sterl and Caires, 2005). The first major development based on this database was the observation that the trends in the 90%-iles and 99%-iles of the significant wave heights showed the same spatial patterns as those in the mean, but had higher slopes. The maximum trends in the mean significant wave height were about 4 cm per year and in the 99%-iles about 7 cm per year. These trends were related to similar trends in wind speed, the upper limits for which were about 6 cm/s per year for the mean and 12 cm/s per year for the 99%-iles.

A thorough comparison of modelled wind speeds and significant wave heights from several reanalysed databases against measurements (incl. short-scale features, monthly means, long-term trends and variability) revealed that differences between wave data sets were larger than differences between the wind speed data sets (Caires et al., 2004). This feature mirrors an analogous phenomenon probably first established for the northern Baltic Sea a few years ago (Broman et al., 2006) and to some extent reflected in terms of a certain mismatch of numerically modelled and visually observed wave properties in Papers III and IV. The analysis led to the recommendation to use the ERA-40 data set for detailed description of wind speed and significant wave height in global studies but to use the complementary AES40 data set for studies in the North Atlantic. For the most adequate description of the largest significant wave heights in strong storms it was suggested to use the PWA-R or the CS01 data sets because ERA-40 poorly presented high quantiles. Long-term features, however, seemed to be equally presented in all data sets.

Caires and Sterl (2005a) presented an analysis of global 100-year return values of wind speed and significant wave height using ERA-40 data corrected to some extent on the basis of measurement data. The most extreme wave conditions were shown to occur, as expected, in the storm track regions. The globally highest return values of wave heights were predicted for the North Atlantic.

As ERA-40 significant wave height data suffer from some limitations, a new nonparametric method for correcting the modelled data has recently been suggested by Caires and Sterl (2005b). In comparison with measurements, the corrected data (so-called C-ERA-40) show a clear improvement in bias, scatter and quantiles. The method has also made it possible to remove several inhomogeneities present in the ERA-40 data set. Currently, ECMWF is producing an interim reanalysis and only NCEP/NCAR reanalyses are continuously updated (Weisse and von Storch, 2010).

1.2. North Sea

The first systematic contemporary studies of the wave climate changes in the North Sea (Bacon and Carter, 1991) revealed an increase in mean wave heights from about 1960 to a peak around 1979–1980. The mean wave height for 1984 was 13% lower than the peak but winters at the end of the 1980s produced severe conditions in the northern North Sea.

Wind statistics derived for the North Sea using data from the NCEP/NCAR reanalysis for the period from 1958 to 1997 revealed an increase in annual mean wind speed of about 10% during these 40 years (Siegismund and Schrum, 2001). This increase was mainly restricted to the period from October to March. It was accompanied with an intensification of west-southwesterly winds in the winter season (October to January) for the whole North Sea, an extension of the winterly wind climate towards February and March during the period from 1988 to 1997 and a positive trend for southerly winds in 1958–1987 in the northern North Sea.

Further analyses of the long-term wave height changes in the North Sea revealed a positive trend in significant wave heights in 1955–1999, mainly in the northern part of the North Sea (Vikebø et al., 2003). However, the overall time series (1881–1999), one of the longest used in similar analyses, did not show any distinct trend: the increase in the 20th century was no more dramatic than the decrease which occurred from 1881 towards the beginning of the 20th century. An analysis of the annual maximum significant wave height, however, strongly indicated increasing wave heights and rougher wave climate at the stations off the coast of mid-Norway during the second half of the 20th century.

A number of numerical hindcasts of the North Sea wave conditions have recently been performed by scientists of the Institute of Coastal Research, Geesthacht. Weisse et al. (2002) presented preliminary results from a 40-year (1955–1994) wind and wave hindcast for the southern North Sea using wind fields from NCEP reanalysis.

Analysis of wave conditions over a longer period 1958–2001 showed that the average number of storms had increased over the southern North Sea, but the increase had attenuated later (Weisse et al., 2005). This result matches well the conjecture of an analysis of storm-related sea level fluctuations from a numerical hindcast for the years 1958–2002 for the North Sea coast (Weisse and Plüß, 2006). Although there were considerable variations from year to year and over the entire period, no significant increase in the severity of storm surges was found.

The most recent study of the extreme wave conditions for 1958–2002 in the North Sea showed that the wave hindcast reasonably reproduced observed extreme value statistics except for stations located in areas with complex topographic features (Weisse and Günther, 2007). The key conclusion of the study was that the wave conditions in question showed substantial spatial variation. For example, the annual 99%-ile wave height had increased off the Netherlands, the German and the Danish coasts, with a maximum of up to 1.8 cm per year off the East Frisian coast. Decreasing extreme wave heights of up to 0.6 cm per year were found to occur simultaneously in some areas off the British coast. Weisse and Günther (2007) inferred that the increase in the 99%-iles of wave heights in the south-eastern North Sea was mainly caused by an increase in the number of extreme events, whereas their duration and intensity revealed no significant changes. Finally, the studied parameters exhibited quite a complex temporal behaviour; for example, the 99%-ile wave heights increased until about 1990–1995 and decreased afterwards.

The information about the wave climate of the northern Baltic Proper mostly relies on a few measurement sites (Figure 2). Instrumental measurements have been carried out in this area since the end of the 1970s. The scarcity of such experiments can be partially explained by the fact that experimental studies of wave conditions are a very complex task. The information is particularly fragmentary for the eastern part of the Baltic Proper. 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), instrumental wave measurements are almost missing for the Estonian coastal area except for sporadic measurements made with pressure-based sensors (Soomere, 2005). Only recently, data covering five months of wave fields near Saaremaa (Suursaar and Kullas, 2009) and one year near the north-eastern coast of Estonia (Ü. Suursaar, personal communication, 2009) have become available. The situation is the same for the nearshore of Latvia and Lithuania: no instrumentally recorded wave data is available in international scientific literature for this section of the eastern Baltic Sea coast. The shortages in forcing data for wave modelling and the lack of long-term instrumentally measured wave time series from the Baltic Proper make all available wave data sets an important source for the wave research in the Baltic Sea.

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

As a recent overview of the contemporary wave measurements in the northern Baltic Sea (Soomere, 2008) is available, I sketch here only shortly the basic features of the relevant data sets and underlying technologies of measurements and observations.

1.3. Instrumental wave measurements in the northern Baltic Sea

Almagrundet

The data from Almagrundet (1978–2003, 59°09′ N, 19°08′ E, Figure 2, Broman et al., 2006) form the longest instrumentally measured wave data set in this region. Almagrundet is a shoaling area (with the minimum water depth of 14 m) located about 10 nautical miles south-east of Sandhamn in the Stockholm archipelago. It is sheltered from a part of dominating winds (in particular, the fetch length for winds from the south-west, west and north-west is quite limited at this site).

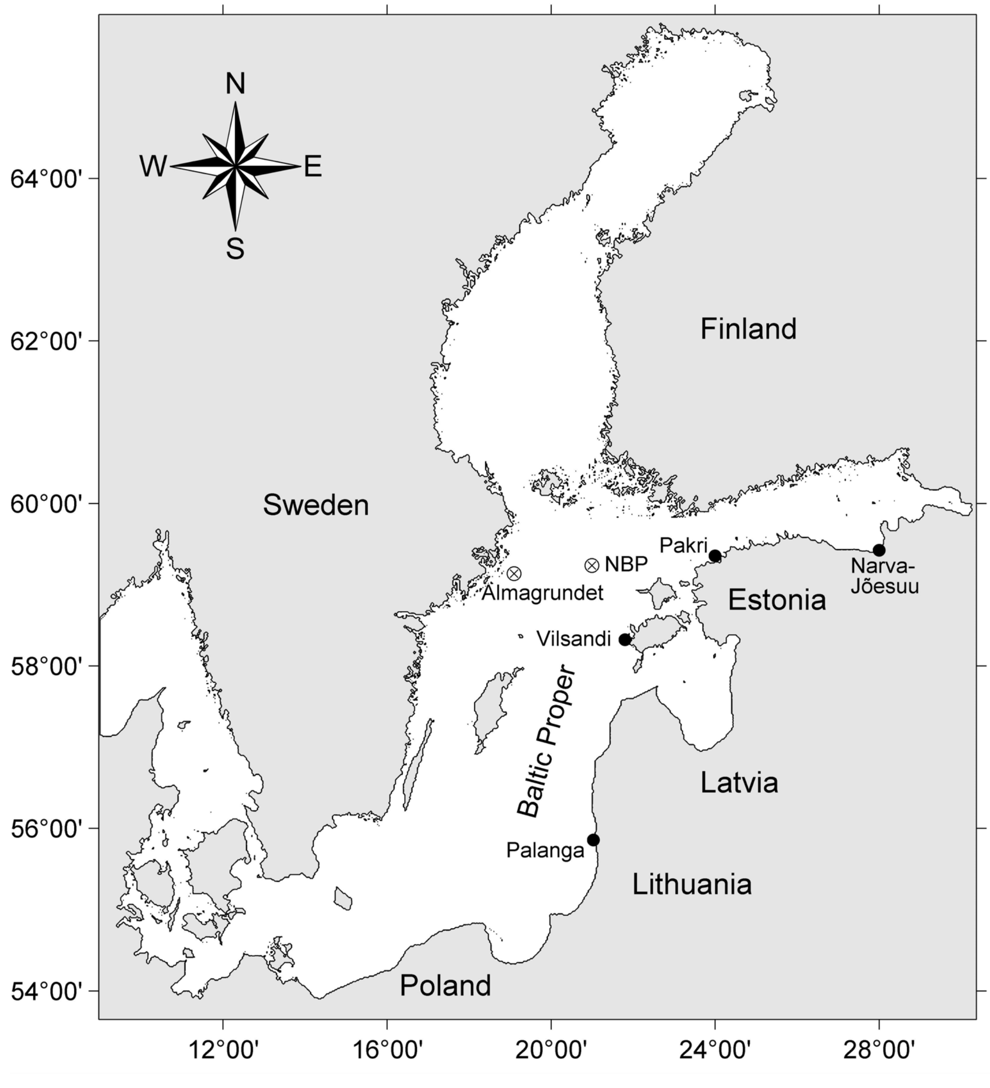

Figure 2. Location of coastal observation sites (filled circles) and instrumental measurement sites (crossed circles) from where the data is used in this study

The above-discussed anisotropy of the Baltic Sea wave fields has caused some discussion about whether the data correctly represent the open-sea wave conditions (Kahma et al., 2003). There has been also some doubt concerning the quality of wave data for one of the devices (Broman et al., 2006). The data from 1978–1995 reliably describe the wave properties in this region. Later recordings in 1993–2003 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). Still, the data constitute one of the most valuable data sets for the Baltic Sea because of the long temporal coverage and good resolution (1 h when available).

An upward-looking echo sounder from Simrad was placed at a depth of about 30 m (where the typical Baltic Sea waves are insignificantly affected by the seabed) in 1978 (Mårtensson and Bergdahl, 1987) and was active until mid-September 1995. An analogous device from WHM was installed in a neighbouring location at a depth of 29 m in 1992 which produced usable data in 1993–2003 (Broman et al., 2006). The position of the water surface was sampled over 640 s each hour. Single waves were identified with the zero-downcrossing method (IAHR, 1989). An estimate of the significant wave height H_S was found from the 10th highest wave in a record under the assumption that wave heights are Rayleigh distributed. Wave components with periods of less than 1.5 s as well as the data probably reflecting wave interference and breaking waves and possibly very steep waves were discarded (Mårtensson and Bergdahl, 1987).

Bogskär

The most reliable information about wave statistics stems from directional wave buoy measurements at Bogskär between 1982 and 1986 and in the northern Baltic Proper between 1996 and 2000 (Kahma et al., 2003). Both measurement sites are completely open to the sea and thus represent well the open sea wave properties.

A non-directional waverider was operated in 1983–1986 near Bogskär at 59°28.0′ N, 20°21.0′ E (Kahma et al., 2003). The wave properties were measured hourly. This device as well as contemporary spectral wave models estimate the significant wave height as $H_S = 4\sqrt{m_0} \approx H_{1/3}$, where m_0 is the zero-order moment of the wave spectrum (the total variance of the water surface displacement; e.g. Komen et al., 1994).

The total measuring time at Bogskär was about 2 years of uninterrupted measurements. The measuring times, however, are concentrated in the autumn season and thus represent well the wave climate during relatively windy months (Soomere, 2008). The basic properties of the measured wave conditions are available in Kahma et al. (2003).

Northern Baltic Proper

The most representative wave data for the northern Baltic Proper (NBP) stem from a directional waverider which was operated by the Finnish Institute of Marine Research (FIMR) at a depth of about 100 m (Figure 2, 59°15′ N, 21°00′ E) from September 1996 during the ice-free seasons (Kahma et al., 2003). After the splitting of the FIMR in 2008, the waverider has been operated by the Finnish Meteorological Institute (FMI). This device estimates the significant wave height, as above, as $H_S = 4\sqrt{m_0} \approx H_{1/3}$. Although this time series (available only for 1996–2002; Kahma et al., 2003) is not long enough for determining the long-term changes in wave properties in terms of climatological information (WMO, 2001), these data serve as the most reliable information about the main characteristics of wave fields in the open sea. The wave statistics and scatter diagrams for this measurement site are extensively used below in comparisons of modelled and measured wave properties.

Gulf of Finland

Directional wave measurements were also conducted at two different sites in the Finnish waters of the Gulf of Finland in 1990–1991 and 1994 (Kahma and Pettersson, 1993; Pettersson, 2001). Although they have been carried on since November 2001 at a location near Helsinki (Soomere et al., 2008) during the ice-free seasons, the relevant information has not been made available in international publications. These measurements have, however, considerably increased the awareness of specific wave conditions in semi-enclosed sub-basins of the Baltic Sea, as they have been used as the basis for identification of a frequent generation of systems of relatively long and high waves propagating along the axis of the Gulf of Finland in so-called slanting fetch conditions (Pettersson et al., 2010).

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

A good source of the open sea wave information is visual observations from ships (Hogben and Lumb, 1967). Wave climate changes estimated from data observed from merchant ships are consistent with those shown by the instrumental records (Gulev and Hasse, 1998, 1999). Although visual observations from the coast are less frequently used for wave climate studies, historical visual wave data from the north-eastern (downwind) parts of the Baltic Proper form an extremely valuable data set for identification of changes in the local wave climate because of their relatively high quality and extremely long temporal coverage.

Visual wave observations include 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 in the immediate vicinity of the observation point and for a limited range of directions, frequently miss long-wave systems (Orlenko et al., 1984), usually have a poor spatial and temporal resolution and many gaps caused by inappropriate weather conditions or by the presence of ice, may give a distorted impression of extreme wave conditions, etc. For example, visual observations from Tallinn Harbour usually did not reflect any swell-dominated wave fields, although such fields formed a large part of wave conditions in Tallinn Bay (Soomere, 2005).

The basic advantage of visual observations is the large temporal coverage. Regular observations started in 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).

Vilsandi, Pakri and Narva-Jõesuu

A coastal site reasonably reflecting the open sea wave conditions for the dominant wind directions in the northern Baltic Proper is operated by the Estonian

Meteorological and Hydrological Institute (EMHI) at the Island of Vilsandi (58°22′59″ N, 21°48′55″ E, Figure 2). This site gives inadequate data for easterly winds. The features of the site, the routine of observations and a description of the data set can be found in Soomere and Zaitseva (2007). Below we shall use data from the years 1954–2008.

Another site where the 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 2). Pakri is the only wave observation site on the northern coast of the Estonian mainland which is largely open to waves generated in the Baltic Proper and where the observed waves reflect well the wave conditions in the open sea (Zaitseva-Pärnaste et al., 2009). The average depth of the area at Pakri over which the waves were observed was 8–11 m.

The third time series of the observed wave conditions stems from the Narva-Jõesuu meteorological station in the eastern part of the Gulf of Finland (59°28′06″ N, 28°02′42″ E, Figure 2) in Narva Bay. The site from which sea observations are made is located to the west of the station. The area in which waves are observed is 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 and shorter than in the Baltic Proper, waves do not break at the observation area during most of wave conditions. The site is fully open to waves propagating from the north-western direction and almost open to waves approaching from west to north. The height of the observation platform is 12.8 m above the mean sea level, thus wave observation conditions are even better here than at Vilsandi.

Palanga, Klaipeda and Nida

Observations at the Lithuanian coast were made using the same methodology as at the Estonian coast (Kelpšaite et al., 2008). The Palanga (55°55′ N, 21°03′ E, Figure 2) and Klaipeda (55°42′ N, 21°07′ E) observation sites are open to dominant wind directions from south-west to N-NW. At Palanga, observations were made from the Palanga Sea Bridge which extends 470 m offshore. The observer was standing 3 m above sea level. The water depth in the observation area was 6–7 m. At Klaipeda, observations were made from the coast where the observer was standing about 3 m above sea level. The area where wave properties were observed lies 500 m off the coast. The observation site at Nida (55°18′ N, 21°00′ E) was fully open to waves approaching only from W to NNW. The observer was standing at a turret located 7 m above the mean sea level at the coast. The observation area was about 700 m from the coastline where the water depth is 6–7 m.

All sites listed in this section 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 the finite-depth effects than much longer ocean waves at similar depths, the sheltering effect of the shoreline and the relatively small water depth of the observation sites may at times significantly alter the local wave regime compared to that in the open sea due to the shoaling and refraction of the waves.

Wave observations at Estonian sites started in 1954 and were performed up to three times a day. Observations at the Lithuanian coastal sites started also more than half a century ago but only a small fraction of the diaries have been digitized (Kelpšaite et al., 2008).

The wave observation routine and technology was identical at all visual observation sites. The features of the sites at Vilsandi and Pakri, a detailed overview of the routine of observations and a description of the data sets can be found in Soomere and Zaitseva (2007), Zaitseva et al. (2009) and Paper I. Further details concerning observations at Narva-Jõesuu are available in Papers III and IV. Here I only present the key features of the observation routine.

Observations were only made in daylight. The initial observation times (7:00, 13:00 and 19:00 Moscow time, or GMT +3 h) were shifted to 6:00, 12:00 and 18:00 GMT in 1991. This shift apparently did not cause any substantial inhomogeneity in the time series of the daily mean wave height, the property mostly used below. The interval between subsequent observations (6–24 h depending on the season) is often much longer than the typical saturation time of rough seas in the northern Baltic Proper (about 8 h; Soomere, 2001) or the duration of wave storms (that seldom exceeds 10 h; Broman et al., 2006; Lopatukhin et al., 2006). The data, however, are reported to well represent the general features of the Baltic Sea wave fields: relatively low overall wave activity, short wave periods and substantial seasonal variation in wave conditions (Soomere and Zaitseva, 2007).

The observational procedure resembles the classical zero-crossing method. The observer noted the five highest waves during a 5-min 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 even higher waves. The highest single wave H_{max} and the mean height H of these five waves were filed.

Given the typical wave period in the coastal zone 3–4 s (Broman et al., 2006; see also the analysis below), the resulting mean wave height was actually the average height of top 5–7% of the waves and thus quite close to the maximum wave height. As the observers' estimates well represent the significant wave height (Gulev and Hasse, 1998, 1999), H (or H_{max} when this measure is missing) has been used as an estimate of the significant wave height. Both the mean and maximum wave heights were filed until about 1990, whereas the maximum wave height was, on average, only 6% higher than the mean wave height at Vilsandi (Soomere and Zaitseva, 2007). In the analysis below, the mean wave height is used; when it was missing, it was substituted by the maximum wave height. As the potential difference is much smaller than the accuracy of determination of the wave height, such substitution insignificantly affects the wave statistics.

The wave period was determined as an arithmetic mean from three consecutive observations of the passing time of 10 waves during each observation. 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 suggests that the visually observed estimate of the wave height well represents the significant wave height, whereas the estimated wave period is only a few tenths of seconds shorter than the peak period (Gulev and Hasse, 1998, 1999).

The digitized data sets were first checked for internal consistency (e.g. whether large wave heights are associated with relatively large periods). In order to remove the bias caused by a systematically larger number of observations per day during relatively calm spring and summer seasons, the analysis below is based on the set of daily mean wave heights as in previous studies (Soomere and Zaitseva, 2007; Zaitseva et al., 2009). As average wave periods usually vary insignificantly over different seasons, their analysis is based on the entire set of single consistent observations.

1.5. Wave climate studies for the northern Baltic Sea

I start the description of the wave climate studies in the water bodies surrounding Estonia from the available analyses of visually observed and instrumentally measured wave data. Studies into wave properties in the Baltic Sea extend back for many decades. Valuable wave data and statistics are presented in literature published in the former USSR (Rzheplinsky, 1965; Rzheplinsky and Brekhovskikh, 1967; Davidan et al., 1978, 1985). The use of these sources for the analysis of the wave properties in this basin is, however, not straightforward because of the potential changes that may have occurred in the wave fields over decades.

Extreme wave heights and sea levels in the northern Baltic Proper and in the Gulf of Finland during a very strong storm of November 2001 were described by Pettersson and Boman (2002). 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. A similar short note (2000) reported that in December 1999 the significant wave height twice exceeded 7 m in the northern Baltic Proper.

A thorough analysis of wave measurements at Almagrundet performed in 1978–2003 revealed that the annual mean wave height for the years 1978–1995 showed a linear rising trend of 1.8% per year (Broman et al., 2006). For these years, a good match was identified between the temporal behaviour of the Utö wind data and the Simrad wave data. The trends extracted from WHM data for 1993–2003 were found indistinct and less reliable. In particular, the rapidly falling trend in the annual average wave height in 1999–2003 did not match the relevant wind data (that showed a further increase in the annual mean wind speed) and it was thought to be fictitious.

A review of the average wave conditions, their seasonal cycle and decadal variations, and extreme wave storms in the northern Baltic Sea was provided by Soomere (2008). It was based on long-term wave measurements at Almagrundet, visual wave observations at Vilsandi (1954–2005), and on wave statistics from Bogskär (1982–1986) and from the FIMR waverider in the northern Baltic Proper (1996–2000). The study revealed that no overall increase in the average wave height occurred in the northern Baltic Proper during the second half of the 20th century. The annual mean wave heights revealed substantial, almost synchronous behaviour at Almagrundet and at Vilsandi: the rapid increase in the 1980s and until the mid-1990s was replaced by an equally rapid decrease in about 1997. The frequency of extreme wave storms was found to be largely unchangeable during the last 30 years. Such storms have occurred roughly twice a decade.

Visual observations from three different Lithuanian coastal sites during 1993–2005 were compared with data from Almagrundet and Vilsandi by Kelpšaite et al. (2008) with the goal of identifying sub-decadal and decadal changes in the wave climate in the south-eastern section of the Baltic Proper. The main conclusion was that, notwithstanding what happened in the northern Baltic Proper, wave activity did not change much at the south-eastern coast of the Baltic Sea in the 1990s. The overall wave activity showed a very slight increase at the Lithuanian coast.

The role of independent local numerical reconstructions of the wave climate for the Baltic Sea is especially important because similar reconstructions for the North Atlantic and the North Sea mostly cannot be directly extended to the Baltic Sea basin because of their poor spatial resolution. On the other hand, the wave properties in the Baltic Sea can be modelled with the use of local models, because the waves from the rest of the World Ocean practically do not affect this water body. As the required resolution of both wind and wave models is higher than in the North Sea, the output of different versions of local atmospheric models such as HIRLAM (High Resolution Limited Area Model) or relatively high-resolution wind fields derived from geostrophic winds are used in the simulations.

The pattern of predominant winds (Mietus, 1998; Soomere and Keevallik, 2001) and the geometry of the Baltic Sea suggest that the highest and longest waves occur either at the entrance to the Gulf of Finland, off the coasts of Saaremaa, Hiiumaa and Latvia, or along the Polish coasts. Wave data from the northern parts of the Baltic Proper thus adequately represent both the average and the roughest wave situations in a large part of the region. Below I only consider studies that have also covered the northern Baltic Sea.

A number of different wave models, starting from simple fetch-based models up to the most contemporary spectral wave models, have been implemented for the Baltic Sea conditions (Tuomi et al., 1999; Soomere, 2001; Jönsson et al., 2002; Alari et al., 2008; Kriezi and Broman, 2008; Suursaar and Kullas, 2009). There has been much discussion as to whether the most widely used third-generation wave model WAM (Komen et al., 1994) is suitable for the specific conditions of the Baltic Sea where short periods of the most frequent waves, relatively shallow water and complex geometry (that request very high spatial and spectral resolution and thus a very small time step) put the capacity of this model on its limit.

The results of this model, forced by winds from the EUR-HIRLAM model, were verified against the measurements from two buoys – east of Gotland and in the northern Baltic Proper for the year 1998 (Tuomi et al., 1999). The comparisons between the modelled and measured wave heights showed a good agreement. The WAM model (Cycle 4) only tends to slightly underestimate the wave heights in the northern Baltic Proper. The main conclusion was that in the open sea the models performed well but problems might occur near the coasts. These problems were revisited for the conditions of Tallinn Bay where the model was found to be adequate as close to the coast as about 200 m and at as low depths as 5 m, provided the spatial and spectral resolutions were appropriate (Soomere, 2005). It was, however, recommended to extend the frequency range of waves (about 0.5 Hz in the standard configuration) up to about 2 Hz in order to properly resolve the growth of short waves in low wind conditions after calm situations.

A recent validation experiment of the WAM model was forced by ERA-40 and RCA (Rossby Centre regional climate model) winds (Berg, 2008). The results of the model runs were compared with measured data from six buoys. The model tends to slightly underestimate wave heights, whereas the rate of underestimation increases with increasing wave height. The differences between simulations using ERA-40 and RCA winds were notable: ERA-40 showed slightly better results.

The first contemporary reconstruction of the wave climate in the Baltic Proper for the years 1947–1988 using the NCAR data set (Mietus and von Storch, 1997) showed seasonal (annual) and multi-seasonal (multi-annual) variations in the reconstructed time series but revealed no statistically significant long-term trends.

Wave climate over 19 years (1978–1996) was derived with the use of the wave model WAVAD at four locations in the southern and eastern Baltic Sea – in the Pomeranian Bay and outside the Polish, Lithuanian and Latvian coasts (Blomgren et al., 2001). Validation of the model was done against measurements at three locations in the southern Baltic Sea. The model was driven by wind fields covering the entire Baltic Sea derived from five time series of wind speed and direction recorded at different Swedish meteorological stations. The central result of the study was establishing the mean and maximum wave heights and directional distribution.

There have been attempts to reconstruct the key features of the entire Baltic Sea wave fields on the basis of relatively short simulations. For example, the second generation spectral wave model HYPAS (Hybrid Parametrical Shallow water; 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 model was forced by MESAN winds (Häggmark et al., 2000) on a 22 km×22 km grid. The quality check of the modelled wave fields was performed with the use of wave measurements from five automatic stations operated by the SMHI. The model was found to slightly underestimate the highest waves. The highest modelled waves were found in the outer part of the Skagerrak, at the border to the North Sea and in the central and southern parts of the Baltic Proper. A more detailed study of spatial and temporal variations in the surface waves in this environment was presented in the doctoral thesis by Jönsson (2005).

The results of the modelling of waves and currents in the Baltic Sea and the Gulf of Gdansk by using three different models (WAM, SWAN (Simulating Waves Nearshore; Booji et al., 1999) and POM (Princeton Ocean Model)) during several storms in the years 1998–2001 showed a good agreement between the modelled and measured data (Cieslikiewicz and Herman, 2002). The meteorological data (3-hourly gridded wind with a resolution of 0.15°×0.15°) for the model were prepared by the Centre for Mathematical and Computational Modelling (Warsaw). As in the Gulf of Gdansk, no measured data were available; the results were verified by means of comparisons of different models run on the same grid. The models gave very similar results.

A study of extreme wave conditions in the northern part of the Baltic Sea during windstorm Erwin/Gudrun in January 2005 revealed that the earlier estimates for the maximum wave heights that may occur in the northern Baltic Sea (8–8.5 m as discussed above) are underestimated (Soomere et al., 2008). Waverider measurements reported the greatest significant wave height of 7.2 m in the northern Baltic Proper and measurements by a pressure sensor established the maximum significant wave height of 4.5 m near Naissaar in the Gulf of Finland. A thorough comparison of the measurements in the open northern Baltic Sea with the output of three state-of-the-art operational wave models from Finnish, Danish and German marine and weather services revealed that the roughest wave conditions under this storm apparently occurred off the coasts of Saaremaa and Latvia where the significant wave height was about 9.5 m.

Several recent efforts towards the development of a hindcast wave database and a wave database based on future climate scenarios are currently in progress (Kriezi and Broman, 2008; Cieslikiewicz and Paplinska-Swerpel, 2008). The SWAN model forced with wind data prepared with the use of the RCA model is employed for numerical hindcast for the entire Baltic Sea, including also the Kattegat and Skagerrak (Kriezi and Broman, 2008). The results were validated by using also MESAN winds for part of calculations. The performance of the wave model with MESAN winds was found to be very good, while the use of the RCA winds necessitated certain corrections of the wave heights that were generally underestimated during extreme storms. Today, preliminary results for one year (1999) have been presented to the public (Kriezi and Broman, 2008) and the long-term run (45 years from 1961 to 2005) is apparently in progress.

The first results of a similar 44-year hindcast for a somewhat different time period (1958–2001) for wind wave fields over the entire Baltic Sea were recently reported by Cieslikiewicz and Paplinska-Swerpel (2008). In these calculations, the WAM model was forced by hourly gridded winds provided by the GKSS atmospheric model REMO (with a resolution of 0.5°×0.5°) forced by the NCEP reanalysis. According to preliminary information, in general the agreement between the hindcast and measurements was quite good but the model tended to overestimate wave heights during storm peaks. The modelled wave heights were also found to correspond well to satellite observations.

Wave climate studies in Estonian coastal waters

Contemporary wave models have been used for reconstruction of wave properties in Estonian coastal waters for about a decade. The WAM model was implemented in a relatively high resolution (1 nautical mile) during hydrometeorological studies of possible sites of the Saaremaa deep harbour (Soomere, 2001). The properties of saturated wave fields during typical and extreme storms in the neighbourhood of Saaremaa (mostly calculated on the basis of wind information recorded at Vilsandi and Sõrve meteorological stations) revealed substantial anisotropy of both wind and wave fields in the north-eastern Baltic Sea (Soomere, 2003).

A simplified method for rapid calculation of main properties of the local wave climate, based on the high-resolution triple nested WAM model and high-quality marine wind data, was implemented for the Tallinn Bay area by using wind information from Kalbådagrund collected in 1991–2000 (Soomere, 2005). This study revealed to some extent the magnitude of spatial variation in wave properties in semi-sheltered bays of the North Estonian coast and made an attempt to quantify the extremely high temporal variability of wave fields in such bays.

Further studies of wave conditions and their long-term variations in the northern Baltic Proper in 1954–2005, which were based on visual observations at Vilsandi, revealed a quasiperiodic behaviour of the annual mean wave height (Soomere and Zaitseva, 2007). The wave activity was found to vary insignificantly in the 1960s and 1970s. It increased considerably in the 1980s and started to decrease again in about 1997. The central outcome was that no clear increasing trend in significant wave height can be identified at Vilsandi. The qualitative match of the long-term variations in wave properties at the opposite coasts of the Baltic Sea allowed of the conclusion that the hypothesis by Broman et al. (2006) about the overall change in the wind direction as a major driver of wave climate changes at Almagrundet is apparently not justified.

The basic properties of wave climate in the nearshore of the Western Estonian Archipelago have recently been reconsidered using a simple fetch-based SMB (named after Sverdrup, Munk and Bretschneider) model forced with wind data from the Vilsandi meteorological station (Suursaar and Kullas, 2009). A long-term hindcast of wave heights and periods for 1966–2006 showed quasiperiodic changes in the mean wave heights with the last high stage in 1980–1995. A slightly decreasing overall trend (–0.001 m per year) was established for the entire simulation period. At the same time annual series of 90%-iles and 99%-iles and the annual maxima of simulated wave heights showed an increasing trend. As one-point wind data were used for the hindcast, it is not surprising that the wave and wind properties were highly correlated and that the tendencies in wave heights and variability corresponded to the long-term tendencies in mean and extreme wind speeds at the Vilsandi meteorological station.

A further comparison of the results of visual observations at Vilsandi and Pakri against the outcome of the wave hindcast near Saaremaa using the SMB model (Zaitseva-Pärnaste et al., 2009) revealed substantial mismatch between the modelled wave properties at Harilaid and visually observed wave data at Vilsandi at certain time periods. This feature is not surprising because in many occasions remotely generated waves govern the local wave properties at Vilsandi.

2. Wave model and wind data

2.1. Introduction

As described above, the combination of the complexity of the Baltic Sea wave fields and high requirements for the wind forcing makes it virtually impossible to give an adequate estimate of the Baltic Sea wave climate and its potential changes on the basis of modelling efforts only. As contemporary wave measurements are relatively scarce and short here, the reliable estimates of the wave climate generally require a combination of different data sources with extensive modelling resources. For this reason I make an attempt to merge historical visual observations and numerical hindcast to reveal the seasonal, annual and decadal changes in the basic wave properties in different parts of Estonian coastal waters.

The numerical analysis of wave conditions is thus compared against data extracted from visual observations at Vilsandi in 1954–2005 (Soomere and Zaitseva, 2007), at Pakri in 1954−1985 (Zaitseva-Pärnaste et al., 2009) and Narva-Jõesuu in 1954–2008 (Papers III, IV). The quality of reconstructions of time series in particular storms is analysed against shorter sections of wave data stemming from instrumental measurements at Almagrundet (1978–2003) on the western coast of the Baltic Proper (Broman et al., 2006), and in the northern Baltic Proper for which the wave statistics are available for 1996–2002. Optionally, interrelations between the ice coverage at observation sites and modelled wave data are considered. The basic tool is the third-generation spectral wave model WAM (Komen et al., 1994; WAMDI Group, 1988).

The presentation in this chapter mostly follows Papers I and II and focuses on the wave model and source data used in this study. Section 2.2 describes the most widely used contemporary wave models and discusses the differences between the first-, second- and third-generation wave models. Section 2.3 gives an insight to the particular implementation of the WAM model used in numerical simulations.

One of the key issues in surface wave hindcast is the proper choice of the wind information. This is especially important in the Baltic Sea basin where wind data even from sites that are known to predominantly represent the properties of open sea winds still reveal a major mismatch when compared to measured or visually observed wave data (Broman et al., 2006; Soomere, 2008). This mismatch is also present in reproductions of wave fields with the use of one-point fetch-based wave models (Paper I). Section 2.4 describes the procedure of the adjustment of the geostrophic wind which is used to run the WAM model and some other wind databases for comparisons.

In order to establish uncertainties connected with different wind data, the WAM model was run during a certain interval in parallel with different wind data (geostrophic winds, the MESAN winds and winds from an ECMWF reanalysis). Section 2.5 analyses differences between the WAM ouput (in terms of wave height time series) calculated with the use of three wind databases and compares them to instrumental measurements. It turns out that the MESAN winds give better results for the nearshore of Sweden, whereas the adjusted geostrophic winds lead to a much better match in the open sea. For this reason I have used the geostrophic winds in this study.

2.2. State-of-the-art wave models

Today there exist numerous different wave models, ranging from simple one-point models that basically estimate only the saturated wave properties for the given geometry of the basin considering time series of locally measured wind information to complicated contemporary models that are able to adequately account for all major drivers of wave generation, interaction, damping and transformation.

The most advanced are the so-called spectral wave models that solve the problem of the development, propagation and decay of all components of wave fields. The properties of wave fields are described in terms of a wave spectrum, which shows how the wave energy is shared between components with different lengths and different propagation directions. These models are frequently divided into three generations. First-generation models do not account for non-linear wave–wave interaction and rely on a specific shape of the one-directional wave spectrum. Second-generation models describe this interaction incompletely and generally prescribe the spectral shape for windseas and/or swell. The most advanced are third-generation models that take into account the non-linear interaction along with the majority of other factors affecting the wave fields.

WAM

The wave model WAM has been developed by an international Wave Model Development and Implementation Group (WAMDI Group, 1988; Komen et al., 1994) and is based on a detailed physical description of air/sea interactions. It is one of the best tested wave models in the world, currently used for research and operational applications by more than 100 organizations in the world (Berg, 2008), including the leading operational and scientific centres such as GKSS, ECMWF, FMI, Royal Netherlands Meteorological Institute (KNMI), Deutsche Wetterdienst (DWD), Danish Meteorological Institute (DMI), etc. The model is continuously updated and the most recent version is Cycle 4. This model can be used as a global or regional model and has shown excellent results also in comparisons against other models in local applications (Lalbeharry et al., 2009) Several recent studies have also demonstrated its capacity to reproduce extreme wave conditions in both operational and hindcast mode provided the wind information is adequate (Lalbeharry 2002; Behrens and Günther, 2009).

The WAM model describes the evolution of a two-dimensional (2D) wave spectrum $N(\omega,\theta,\varphi,\lambda,t)$, where N is the wave action density, ω is the relative angular frequency, θ is the wave direction, φ is the latitude, λ is the longitude and t is time. The model integrates the transport equation for the wave spectrum:

$$\frac{\partial}{\partial t}N + (\cos\varphi)^{-1}\frac{\partial}{\partial\phi}(\dot{\varphi}\cos\varphi N) + \frac{\partial}{\partial\lambda}(\dot{\lambda}N) + \frac{\partial}{\partial\omega}(\dot{\omega}N) + \frac{\partial}{\partial\theta}(\dot{\theta}N) = S\,. \tag{1}$$

The first term on the left-hand side of Eq. (1) describes the local rate of change of action density in time, the second and third terms denote the propagation of action density in geographical space (with propagation velocities $\dot{\varphi}$ and $\dot{\lambda}$ along latitudes and longitudes, respectively), the fourth term shows the potential shift of the relative frequency due to variations in depths and currents (with the rate $\dot{\omega}$ of the change in frequency) and the fifth term the joint impact of the depth- and current-induced refraction (with the rate $\dot{\theta}$ of the change in the propagation direction) (Lalbeharry, 2002).

The so-called source term S on the right-hand side of Eq. (1) is given by

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot}\,. \tag{2}$$

While the left-hand terms in Eq. (1) are energy-conserving and only describe the changes in the wave spectrum due to various forms of propagation and transformation of single wave components, the terms on the right-hand side of Eqs. (1) and (2) describe the change in the energy of a propagating wave component due to processes by which energy is transferred to and removed from the wave spectrum. They include wind input S_{in} (energy transfer from wind into the wave field), non-linear interaction between wave components S_{nl}, dissipation due to whitecapping S_{ds} (in the newest versions of the model also due to depth-induced breaking; this feature is not included into the model used in this study) and changes in wave energy due to the bottom friction S_{bot}.

Several other models have been developed on the basis of principles implemented in WAM, for example WAVEWATCH III (Tolman, 2009) by the Environmental Modeling Center of the National Centers for Environmental Prediction (NCEP).

SWAN

The wave model SWAN (Simulating Waves Nearshore; Booij et al., 1999; SWAN team, 2006) is a third-generation spectral wave model that has been developed to estimate wave conditions in small-scale, coastal regions in shallow water conditions and with optional presence of coastal features such as (barrier) islands, tidal flats or estuaries and strong ambient currents (Ris et al., 1999). Similarly to WAM, the SWAN model describes the evolution of the 2D wave energy spectrum in arbitrary conditions of wind, currents and bathymetry. It uses the same formulations for the wave propagation and energy source terms as the WAM model but contains some additional formulations primarily for shallow water (such as the ability to account for triad interactions, depth-induced wave breaking, obstacle transmission and wave-induced set-up) and uses different numerical techniques (SWAN team, 2006).

While the source terms of the WAM model have been carefully balanced for the conditions of long fetches and extensive wave propagation distances in large-scale applications, many configurations of the SWAN model allow for non-balanced regimes (and thus for non-physical properties of resulting wave fields over large run-times). For this reason it is not recommended to run this model on ocean scales unless care is taken about a proper combination of different model options. Although the SWAN model can be configured for runs on large scales (much larger than coastal scales), its main use has been for calculating the transition from ocean scales to coastal scales and especially for coastal applications (SWAN team, 2006). It is customary to couple SWAN and WAM models together so that the open sea wave fields are first calculated by WAM and the relevant boundary conditions used subsequently as input data for SWAN.

2.3. WAM model setup

Following one of the central aims of this research (to adequately reconstruct the wave fields for the entire Baltic Sea), it was decided to use the third-generation wave model WAM as the most reliable and robust tool for calculations of global wave fields. Although this model was constructed for open ocean conditions, it gives good results in the Baltic Sea if its resolution is appropriate and the wind information is correct (Tuomi et al., 1999). The triple-nested, high-resolution version of the model has been used for description of the wave climate of Tallinn Bay based on simulations with the use of one-point open sea wind data (Soomere, 2005). Good results are obtained in quite shallow conditions. The high-resolution version (with a grid step of about 500 m) adequately represents wave properties up to a depth of about 5 m and as close to the coast as about 200–300 m (Soomere, 2005).

For the research below, wave properties over the entire Baltic Sea were computed by using the WAM model Cycle 4 (Komen et al., 1994), over 38 years for 1970–2007. The implementation of this model for the Baltic Sea conditions, which is used in this study, takes the following parameters and processes into account (Soomere, 2005): coastal line of the basin, topographic refraction, spatial and temporal variation in wind properties, wave propagation on the sea surface, quadruplet interactions between wave harmonics, whitecapping, shoaling and wave dissipation in shallow areas due to bottom friction, and interaction of waves and stationary currents.

The model output gives at each grid point at chosen times the following parameters: significant wave height, mean wave direction, mean and peak period, drag coefficient, friction velocity, wind stress fields and 2D wave spectrum.

The bathymetry for the model runs was based on data prepared by Seifert et al. (2001) (http://www.io-warnemuende.de/topographyof-the-baltic-sea.html) and has been adjusted as described in Soomere (2001). The calculation was undertaken over a regular rectangular grid with a resolution of about 3×3 nautical miles. The grid increment is 3′ for latitude and 6′ for longitude. The entire grid contains 239×208 points (11 545 seapoints) and extends from 09°36′ E to 30°18′ E and from 53°57′ N to 65°51′ N. This resolution is somewhat finer than that used in other calculations in the recent past (Jönsson et al., 2002, 2005; Cieślikiewicz and Paplińska-Swerpel, 2008; Kriezi and Broman, 2008).

The wave properties in the Baltic Sea can be modelled with the use of local models, because the waves from the rest of the world ocean practically do not affect this water body (Soomere, 2001, 2008). The model was run uncoupled from the North Sea wave fields on a grid that was truncated in the narrowest parts of the Danish Straits. The hindcast was performed in shallow-water mode with depth refraction (but without depth-induced breaking) in order to match realistic wave propagation patterns over the highly variable bathymetry of the relatively shallow Baltic Sea.

At each seapoint 1008 components of the 2D spectrum were computed. The spectrum contained 24 equally spaced directions (with the angular resolution of 15°) starting from the direction of 7.5° and counted counterclockwise from the direction to the north. The energy of wave components with frequencies ranging from 0.042 Hz (23.9 s) to about 2 Hz (0.5 s) was approximated using 42 frequencies with an increment of 1.1. The extended frequency range up to 2 Hz was used to ensure realistic wave growth in low wind conditions after periods of calm. Such situations are frequent in the Baltic Sea where the standard configuration of the WAM model (that ignores waves with periods below 2 s) does not ensure the realistic growth of relatively short waves (Soomere, 2005). The propagation and source time step were both set to 180 s to ensure numerical stability of the integration scheme. The wave properties were recorded hourly for the entire period of calculations.

2.4. Wind forcing

Geostrophic wind

The wave model was forced with wind data constructed on the basis of geostrophic winds provided by the Swedish Meteorological and Hydrological Institute (SMHI). These data are mainly calculated from the spatial air pressure distribution and, therefore, are free of local disturbances to the air flow by coastal topography and errors in ground wind speed measurements (Keevallik, 2003; Soomere and Keevallik, 2003). On the other hand, the use of these data smoothes out a large number of local variations in wind properties. As geostrophic winds represent global (in the scale of the Baltic Sea) wind patterns, the relevant wave properties reflect well the principal properties of wind patterns on the open sea, which are mostly responsible for the wave climatology.

The wind data were retrieved from the SMHI archived geostrophic winds and were restored from the GRIB format with the use of the CDO (Climate Data Operators) software (Schulzweida et al., 2008). The extracted geostrophic wind components were interpolated from the original grid (that covers a much larger area than the Baltic Sea with a moderate spatial resolution of 1°×1°) to a medium resolution grid (step in space about 6 nautical miles, 123×107 points). The wind input timestep was 6 h before September 1977 and has been 3 h since then. Missing data were constructed with the use of a linear approximation in time for each wind data point. The resulting data reflect the properties of free flow in the atmosphere.

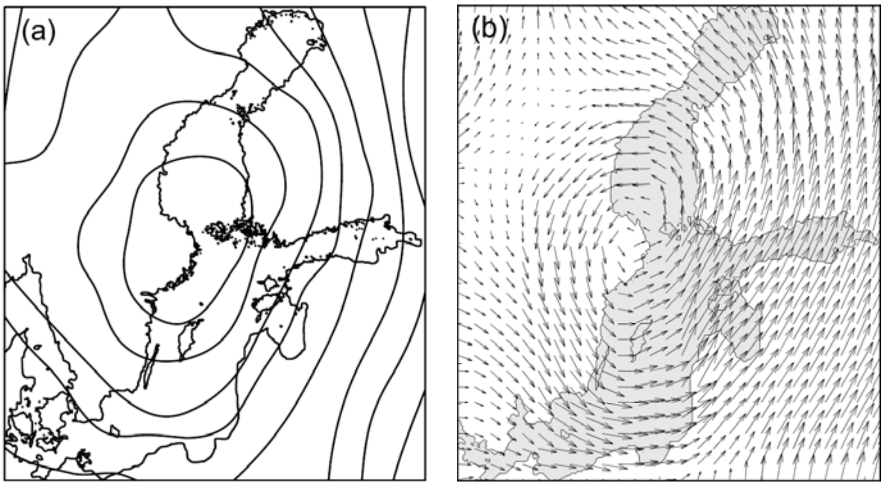

Figure 3. Weather map from the EMHI showing air-pressure isolines (a) and the corresponding wind field restored from the geostrophic wind database (b) at 18:00 GMT, 13 November

An approximation of the near-surface wind at the 10 m level, used as the input to the wave model, was calculated following a standard procedure in which the geostrophic wind speed was multiplied by 0.6 and the direction turned 15° anticlockwise (Bumke and Hasse, 1989). This approximation is becoming increasingly popular in studies of circulation and wave patterns in the Baltic Sea (Andrejev et al., 2004; Zhurbas et al., 2008; Myrberg et al., 2010).

The moderate-resolution gridded wind information covers the entire wave calculation area and was interpolated to the higher resolution wave modelling grid internally in the WAM model. The quality of the retrieved and processed wind data was double-checked with the use of weather maps from the Estonian Meteorological and Hydrological Institute (Figure 3).

MESAN winds and reanalysed ECMWF winds

For comparison of numerically simulated results with instrumentally measured data in the spirit of a similar analysis for the North Atlantic (Cox et al., 1998) we used two alternative wind databases. The MESAN wind database (Häggmark et al., 2000) developed by the SMHI presents hourly gridded wind information since October 1996. The 10 m level wind from the HIRLAM model is used as the first guess field. It is processed by means of optimal interpolation of wind measurements from automatic stations and manual observations into the wind field. This process uses spatially variable structure functions that depend on the horizontal distance between the grids of the first guess field and the measurement locations. As surface roughness and the fraction of land and water in each grid area are accounted for, it is possible to describe local wind variations in rough landscapes and coastal areas to some extent. The grid resolution and time step were 22 km×22 km and 3 h, respectively. Owing to the short temporal coverage, these data were not suitable for climatological studies.

The wave properties were also calculated over several windy weeks in 2001 and 2005 with the use of recently reanalysed wind fields developed by the ECMWF provided by L. Cavaleri and L. Bertotti (personal communication, 2009). The resolution of these data was 0.25°×0.25° and the wind input time step for the WAM model was 1 h.

2.5. Model performance

The performance of the model and the possibilities of the wind data for reconstruction of wave properties were analysed from different viewpoints. Paper I provides a detailed comparison of the significant wave height calculated with different wind data against (i) high-quality waverider measurements in the Baltic Proper during a few stormy weeks, (ii) inverted echo sounder data from Almagrundet during a few weeks and (iii) visually observed data from Vilsandi in terms of wave height time series. A short intercomparison of wave heights modelled with the WAM and SMB models was also performed for the nearshore of Saaremaa in Paper I. Further validation of the model results was conducted in terms of long-term statistics from Almagrundet and the available results of waverider measurements in the northern Baltic Proper (Paper II). This procedure allowed identification of the most adequate wind data for long-term wave calculations.

The match between hindcasts with the use of the WAM model forced with different wind data and the measured data was found to be sensitive with respect to the particular location (Paper I).

In coastal areas of Sweden, simulations using MESAN winds reasonably matched the qualitative course of the observed wave properties and in many cases also satisfactorily reproduced the instantaneous wave height (Figure 4). In this region, the wave heights calculated using geostrophic winds were generally notably smaller (e.g. by 23 cm on average in October 2000). This feature is consistent with observations of many authors (e.g. Zhurbas, 2009) who report that geostrophic winds tend to underestimate wind speeds especially during strong wind events.

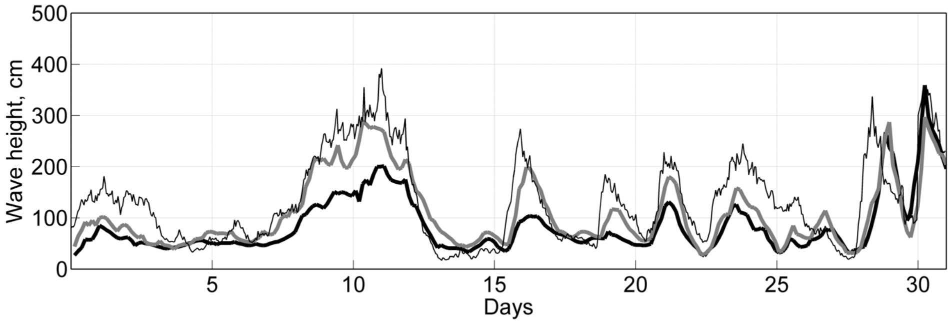

Figure 4. Wave heights (thin line) at Almagrundet (A), October 2000. Grey and bold lines show the hindcast of the WAM model forced with MESAN (M) and geostrophic (G) winds. The biases and standard deviations (cm) are: $bias_{M\text{-}G} = 23.4$; $bias_{A\text{-}M} = 24.1$; $bias_{A\text{-}G} = 47.4$; $STD_{M\text{-}G} = 37.7$; $STD_{A\text{-}M} = 48.3$; $STD_{A\text{-}G} = 72.1$

The wave model reproduces adequately the time series of wave conditions at Almagrundet also when forced with geostrophic winds (Figure 5). The simulations catch all important wave events and their duration in most cases. The maximum wave heights are somewhat overestimated for some storms and underestimated for other wind events. Such mismatches in time series of the measured and modelled wave properties are common in contemporary efforts to model wave conditions in the Baltic Sea (Tuomi et al., 1999; Jönsson et al., 2002; Lopatukhin et al., 2006; Cieślikiewicz and Paplińska-Swerpel, 2008; Soomere et al., 2008).

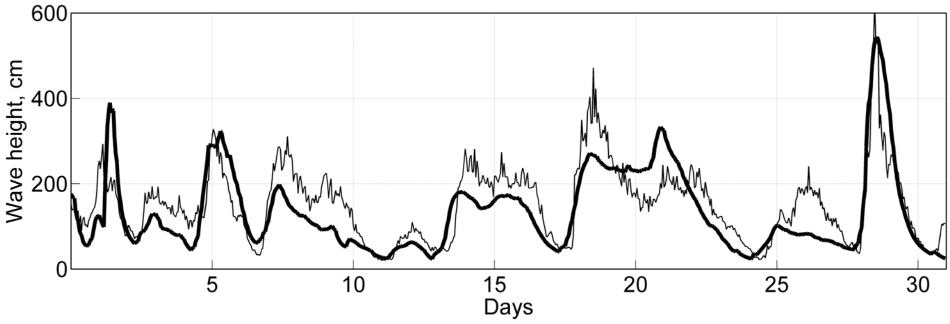

Figure 5. Measured (thin line) and hindcast with the use of geostrophic winds (bold line, no MESAN winds available for this time) significant wave heights at Almagrundet in December 1986. The bias and standard deviation (STD) between the modelled (average 1.34 m) and measured (1.52 m) data were 18.7 and 63.9 cm, respectively. The correlation coefficient was 0.78. Note that the bias and STD between the observed and modelled data at Almagrundet in 1999 were 19 and 45 cm, respectively, for the HYPAS model and MESAN winds (Jönsson et al., 2002)

In our simulations, some deviations probably stem from the choice of the wind forcing that ignores local ageostrophic wind components. There is, however, almost no systematic bias of the results for the typical wind and wave conditions (when the wave heights are about 1 m in the Baltic Sea). The overall average of wave heights is also reproduced reasonably (Figure 6, Table 1).

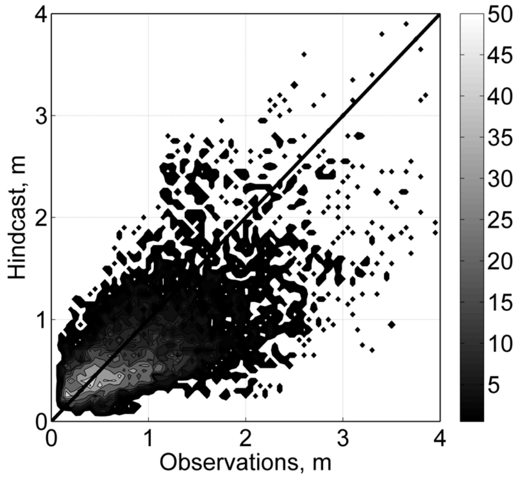

Figure 6. Scatter plot of measured and numerically simulated wave heights at Almagrundet in 1991. The brightness scale shows the number of wave conditions in pixels with dimensions of 0.05×0.05 m. The overall bias is 21.1 cm (observed waves are generally higher) and the STD is 54.1 cm.

Table 1. Average observed or measured and hindcast wave properties at the measurement sites in the northern Baltic Proper and the Gulf of Finland (Broman et al., 2006; Zaitseva-Pärnaste, 2009). For visual observation sites the average of daily mean values is presented (Soomere and Zaitseva, 2007)

Site	Years	Average wave height, m	
		Observed or measured	Hindcast
Almagrundet	1978–1995	0.876	0.714
	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

On the contrary, in the northern Baltic Proper, hindcasts using geostrophic winds frequently gave more adequate results than simulations with the use of MESAN winds (Figure 7). Unlike in the situation at Almagrundet, wave heights obtained with the use of geostrophic winds generally exceeded (on average by 20 cm) those calculated on the basis of MESAN winds.

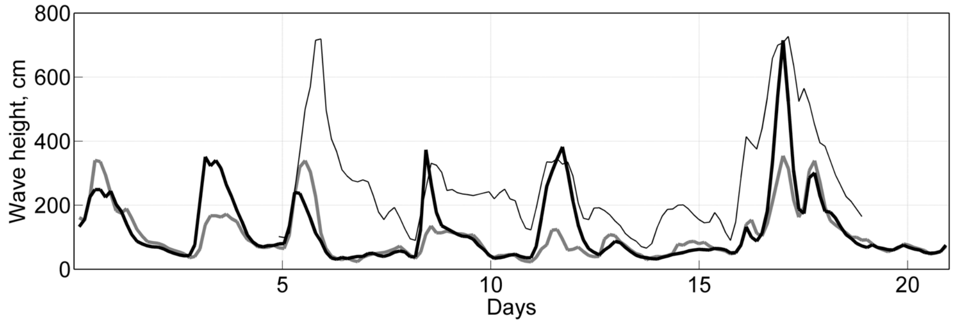

Figure 7. Wave heights (www.fimr.fi/en/tietoa/veden_liikkeet/en_GB/aaltoennatyksia/, thin line) in the northern Baltic Proper at the location of the FMI wave buoy (wb) in December 1999. Notations are the same as for Figure 4. The biases and standard deviations (cm) are: $bias_{G\text{-}M}$ = 11.7; $bias_{wb\text{-}M}$ = 77.0; $bias_{wb\text{-}G}$ = 68.0; $STD_{M\text{-}G}$ = 75.1; $STD_{wb\text{-}M}$ = 205; $STD_{wb\text{-}G}$ = 192

Wave hindcast with the use of the WAM model systematically underestimated the measured wave heights both at Almagrundet and at the FMI wave buoy. The monthly bias, typically, was in the range of 20–40 cm and reached 60–70 cm in windy months such as December 1999.

The largest mismatch between the simulated and measured data usually occurred during extreme wave events. Still, the temporal course of wave heights was qualitatively reproduced. The timing and qualitative course of wave heights hindcast by the WAM model usually acceptably matched the measured data. The timing of the roughest wave conditions was almost perfect at Almagrundet (Figures 4 and 5). The overall timing was also acceptable at the FMI wave buoy (Figure 7). Although the simulations failed to reproduce the duration of rough seas for certain storms, in most cases the model almost exactly reproduced the largest wave height during the wavestorm maximum. This happened more frequently for the FMI buoy and the geostrophic winds (e.g. on 13 January 2005, Figure 8) than for MESAN winds.

The overall course of the significant wave heights simulated with the use of three different wind data (geostrophic, MESAN and ECMWF winds) match well each other but none of the forcings led to clearly better reproduction of measured wave properties (Figure 8, Tables 2 and 3). A typical feature of all model runs is that several storms are almost perfectly reproduced while for others all the forcings in use almost totally failed. The largest mismatch occurred during certain extreme wave events. For example, the use of different forcings led to underestimation by 2–3 m of the extreme wave events on 7 and 9 January 2005.

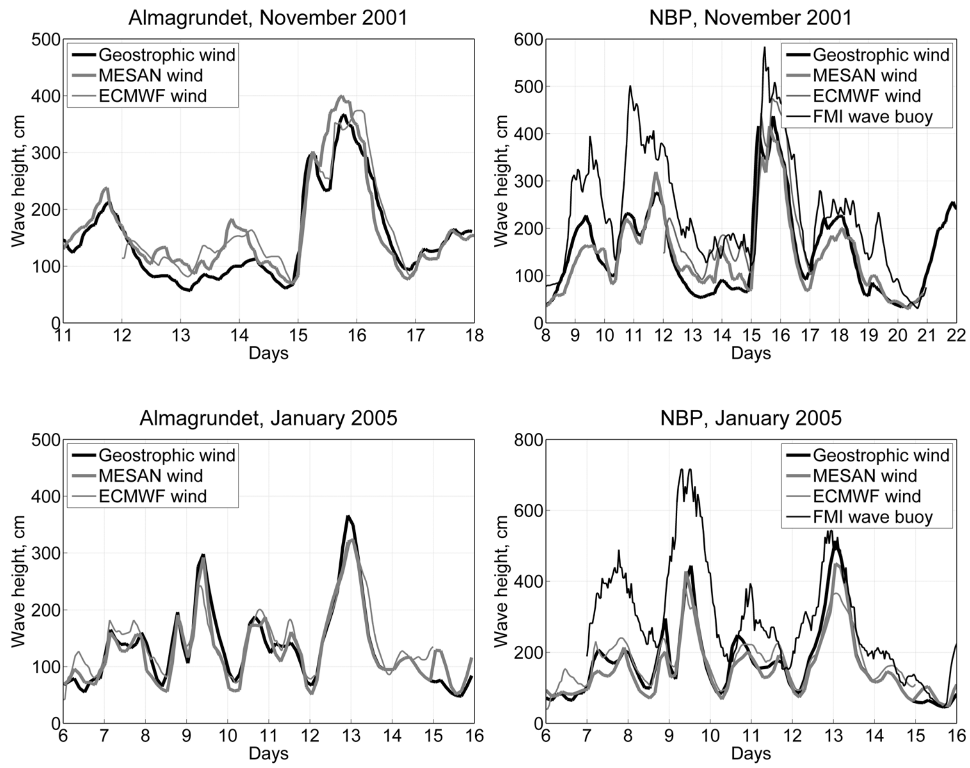

Figure 8. Wave heights in November 2001 and January 2005 at Almagrundet and in the northern Baltic Proper (NBP). Correlation coefficients, biases and standard deviations are presented in Tables 2 and 3

Table 2. Correlation coefficients (*r*), biases (in cm) and standard deviations (STD, in cm) between significant wave height time series based on different winds at Almagrundet

Almagrundet 2001	Geostr.–MESAN	Geostr.–ECMWF	MESAN–ECMWF
r	0.93	0.92	0.92
Bias	19.9	23.7	3.8
STD	39.1	40.8	34.8

Almagrundet 2005	Geostr.–MESAN	Geostr.–ECMWF	MESAN–ECMWF
r	0.95	0.89	0.92
Bias	5.9	6.9	12.6
STD	19.3	31.4	26.5

Table 3. Correlation coefficients (r), biases (in cm) and standard deviations (STD, in cm) between measurements and significant wave height time series based on different winds in the northern Baltic Proper (NBP)

NBP 2001	Geostr.– MESAN	Geostr.– ECMWF	MESAN– ECMWF	Geostr.– measur.	MESAN– measur.	ECMWF– measur.
r	0.94	0.92	0.94	0.86	0.91	0.86
Bias	4.6	10.7	6.1	91.3	86.7	80.6
STD	41.5	54.6	34.5	112.2	101.6	105.5

NBP 2005	Geostr.– MESAN	Geostr.– ECMWF	MESAN– ECMWF	Geostr.– measur.	MESAN– measur.	ECMWF– measur.
r	0.95	0.92	0.93	0.54	0.57	0.63
Bias	17.9	5.1	23.1	189.3	167.5	191.1
STD	34.8	44.3	39.6	215.8	191.1	205.2

It is well known that wind fields reconstructed from atmospheric models frequently underestimate the open sea wind speeds. It is, therefore, not unexpected that runs based on the high-quality ECMWF wind fields result in a certain underestimation of the wave properties. Therefore an alternative source of wind information is necessary in order to reproduce the temporal course of wave fields in particular storms. This conjecture has been highlighted, for example, by studies in the Mediterranean already in the 1970s (L. Cavaleri, personal communication, 2009). A first-order solution would be, for example, the use of altimeter data and, if possible, scatterometer data.

Another interesting feature in Figure 8 is that the highly sophisticated ECMWF model consistently leads to results that insignificantly differ from those obtained with the use of the simplest adjustment of the geostrophic wind.

The presented results of the model validation for different wind data and against a variety of measured and observed wave data described in Papers I and II therefore confirm that the particular implementation of the WAM model and specifically the adjusted geostrophic winds are suitable for adequate representation of the typical wave fields in the Baltic Proper and in these parts of the nearshore of Estonia where the model resolution reasonably reproduces the local bathymetry and geometry. This conjecture essentially relies on the considerably better match of the relevant modelled data in the open part of the northern Baltic Sea. Although the resulting hindcast procedure may underestimate the strength and duration of some strong wave storms, it evidently replicates properly the changes in the wave fields over longer time intervals (>1 month).

The above allows us to assume that the model in use represents well the overall average properties of wave conditions in those Estonian coastal waters that are open to the Baltic Proper. This assumption has been verified against wave statistics constructed from historical visual wave observations at three coastal sites (Paper II). The best match is obtained for long-term averages of wave fields (Table 1).

Their comparison, however, is not straightforward because the time intervals covered by the hindcast and by the observed or measured data only partially overlap. For example, the observed and modelled average wave heights at Vilsandi differ by less than 1 cm (equivalently, by less than 2%) over the period 1970–2007 (Table 1). The match is of almost the same quality at Pakri for 1970–1985 (Zaitseva-Pärnaste, 2009), whereas the overall observed wave height in 1954–1985 is very close to that calculated for 1970–2007 (Table 1). The model, therefore, reproduces well the long-term wave heights for the western and north-western coasts of Estonia.

The results of numerical simulations deviate more from the observed data in relatively sheltered areas where the model tends to overestimate wave heights. At Narva-Jõesuu the modelled average wave height exceeds the observed value by more than 25% (Table 1). There are several reasons for such a deviation. A generic source of error is the insufficient spatial resolution of the wave model in coastal areas (cf. Paper I). The water depth is 3–4 m in the nearshore about 300 m from the coast where the wind wave properties are observed at Narva-Jõesuu. The centre of the closest model grid point, however, is located about 4 km from the site and corresponds to a depth of 7 m. As the waves are generally of moderate height and length at Narva-Jõesuu (see below and in Paper IV), the effect of the depth-induced breaking on the observed wave properties is generally negligible at this site. The overestimation at Narva-Jõesuu may also be due to the joint effect of ignoring the ice cover and the difference between the observation site and the nearest grid point for which the wave properties are calculated. This option is discussed in detail in Paper IV.

There is also a relatively large discrepancy between the measured and modelled wave heights at Almagrundet (Figures 5 and 6, Table 1) where the model systematically underestimates wave heights. As mentioned above, an almost equal bias between the wave heights modelled with the use of the second-generation HYPAS model and MESAN wind fields (19 cm on average in 1999) was identified by Jönsson et al. (2002). A large part of the mismatch probably stems from the poor quality of the Almagrundet wave data (especially in 1993–2003 when the wave height time series contains numerous small but clearly unrealistic peaks (Broman et al., 2006, fig. 7) and the average wave heights, even over small time intervals, are overestimated).

3. Wave statistics and seasonal variations

3.1. Introduction

This chapter presents numerical estimates of key climatological parameters of wave fields in the Baltic Sea and discusses the impact of the largest driver of their variability – the seasonal variation in wind properties in the entire Baltic Sea region. I start from the discussion of spatial patterns of the long-term significant wave height for the entire Baltic Sea (Paper II), which express the basic information about wave properties in different regions.

While numerical hindcast of this quantity shows a good match with its estimates derived from available observations and measurements, there exist much larger deviations in the properties of empirical probability distribution functions describing the occurrence of different wave conditions (Section 3.2).

Further important and highly interesting information is provided by a comparison of the joint 2D distributions of wave heights and periods (scatter diagrams) for numerically simulated, observed and measured data (Section 3.3, Paper III). The analysis confirms, in particular, in quantitative terms the well-known (but as yet discussed only on the qualitative level) specific feature of the Baltic Sea wave fields that have now been shown to be frequently steeper than saturated wave fields. A direct extension of the analysis of these distributions allows establishing a rough estimate for the combinations of wave heights and periods that most probably will occur in the strongest storms.

A large part of this chapter is dedicated to the analysis of certain aspects of seasonal variability of the Baltic Sea wave fields (Section 3.4). A major motivation into these studies is that part of the mismatch between the temporal pattern of the wind speed and wave heights discussed above could possibly be explained by different trends in the wind speed in different months. For example, there has been a clear decrease in the wind speed in summer but a pronounced increase in December and January (Kull, 2005). These changes are not easy to identify, because seasonal variations (for example, the monthly mean) in the wind speed match well with similar variations in wave intensity. This match is evident in both the observed and modelled wave data (Jönsson et al., 2002; Kahma et al., 2003; Broman et al., 2006; Soomere and Zaitseva, 2007; Zaitseva-Pärnaste et al., 2009).

An attempt is made to shed light on this problem by analysing the relationship between wind and wave properties in different months. The key idea is to show the nonlinear dependence of wave heights on the wind speed. Generally, an increase in an already high wind speed results in a larger increase in wave heights than the same increase for a low wind speed (Komen et al., 1994). Therefore, a substantial increase in wave heights because of a growth in the wind speed in a few windy (autumn and winter) months may dominate over the similar decrease in low wave heights in calm (spring and summer) months. This analysis leads to the detection of an interesting mismatch between the wind and wave properties in different months, namely, the windiest months are not necessarily the months with the largest average wave acitivity (Section 3.5, Paper II).

3.2. Distribution of wave heights

The basic features of the spatial pattern of numerically simulated average wave heights in the Baltic Sea over 38 years (1970–2007, Paper II) qualitatively coincide with those discussed in Jönsson et al. (2002). The map of wave intensity in terms of the long-term average significant wave height (Figure 9) is asymmetric with respect to the axis of both the largest sub-basins – the Baltic Proper and the Bothnian Sea. The eastern part of the Bothnian Sea has clearly higher waves (>0.8 m on average) than its western area.

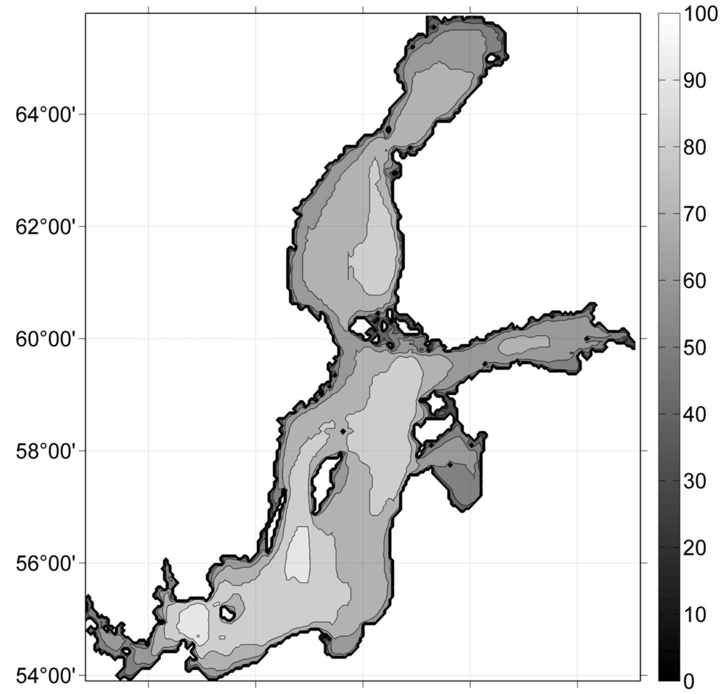

Figure 9. Long-term mean wave height (brightness scale, cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007.

The spatial pattern of the areas of large wave activity has several local maxima and is quite different for the southern and northern parts of the Baltic Proper.

The largest average wave heights occur south of Gotland and east of Öland (around 56° N, 18° E), and in the Arkona basin where the average wave height exceeds 0.9 m over two areas of about 1°×1° in size. The average wave height reaches 1.01 m at one location of relatively low depth in this basin. This is apparently caused by local wave focusing and is not representative of the entire southern Baltic Sea.

The highest wave activity in the northern Baltic Proper occurs along the coasts of Estonia and Latvia. The wave heights are relatively low along the coasts of Lithuania, Kaliningrad district and north-eastern Poland although these areas have a relatively long fetch. The open part of the Bothnian Sea also has quite high waves. The overall wave intensity in the Gulf of Finland is clearly smaller. The average wave heights reach 0.7 m at its entrance and in its central part but are about 0.6 m in the rest of this water body. As shown by one-point forcing of the WAM model with high-quality marine wind data (Soomere, 2005), these values match well a similar estimate for the vicinity of Tallinn Bay (0.56 m). The Gulf of Riga is even calmer with the average wave height slightly exceeding 0.6 m in the open sea.

One of the basic properties of wave climate (which can also be used as a criterion for estimating the performance of the wave model) is the frequency of occurrence of different hindcast, observed and measured wave conditions within a certain range, equivalently, the relevant probability distribution functions (PDF). Here we focus on the analysis of the PDFs for wave heights, because 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)

The comparisons of these distributions are usually performed in terms of matching the bar charts of the relevant empirical PDFs, because more detailed wave statistics are usually not available. Although such charts are quite sensitive with respect to the resolution used (equivalently, thresholds for wave conditions belonging to a particular bar), they are generally as instructive as the comparisons of the time series for selected periods, average wave properties or scatter plots discussed above.

At Almagrundet, the model underestimates the frequency of almost calm conditions ($H_S < 0.25$ m), largely overestimates waves with $0.25 \le H_S < 0.75$ m, and underestimates the frequency of waves higher than 1 m, whereas the discrepancy is less for wave heights $H_S \ge 2.5$ m (Figure 10). This pattern of mismatches is qualitatively similar to that obtained using the 1999 simulations discussed above, where the HYPAS model (Jönsson et al., 2002) overestimates waves with heights $H_S < 0.4$ m and $0.8 \le H_S < 1.4$ m and underestimates waves about 0.5 m high and all wave conditions with $H_S \ge 1.6$ m (Paper II).

The difference between the modelled results and observations probably largely stems from the choice of the step in wave heights at 0.25 m. For example, the frequency of the observed (36%) and modelled (44%) low wave conditions ($H_S < 0.5$ m) differ insignificantly. The same is true for the results of Jönsson et al. (2002). The relative difference is the largest for waves higher than 1 m that seem to be systematically underestimated by the models at Almagrundet. As mentioned above, much of this difference may stem from measurement noise.

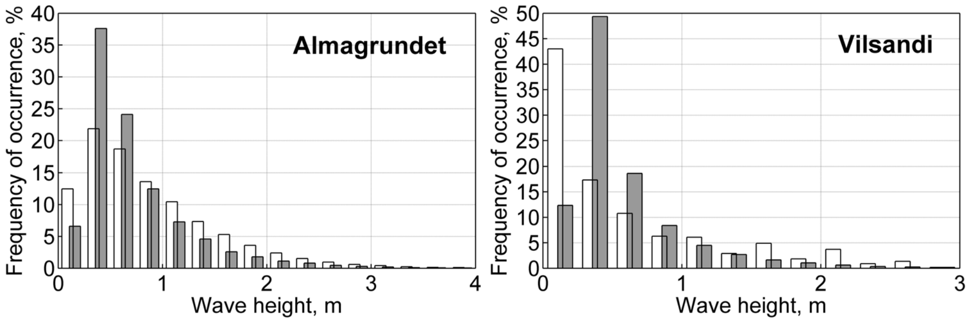

Figure 10. Frequency of occurrence of wave heights at Almagrundet in 1978–1995 (white bars: measurements, Broman et al., 2006; grey bars: WAM model) and Vilsandi (white bars: observations 1954–2008, Zaitseva-Pärnaste, 2009; grey bars: WAM model 1970–2007)

At Vilsandi, the model also underestimates waves <0.25 m and overestimates waves with $0.25 \le H_S < 0.5$ m (Figure 10). The overall characteristics of waves with a height below 0.5 m are again reasonably captured. While waves with heights around 1–1.5 m are sensibly reproduced, the frequency of even higher waves is underestimated. This pattern of mismatches is evident also in simulations with the use of a one-point model forced with Vilsandi winds (Suursaar and Kullas, 2009) and may be an overall feature of wave properties in the coastal areas of Saaremaa.

A slightly different pattern of discrepancies becomes evident in the central area of the northern Baltic Proper and in the coastal area of Lithuania (Figure 11). The model adequately captures the frequency of calm conditions and reasonably hindcasts relatively rough windseas. The frequency of the most typical wave conditions ($0.25 \le H_S < 0.75$ m) is, however, significantly overestimated by the model.

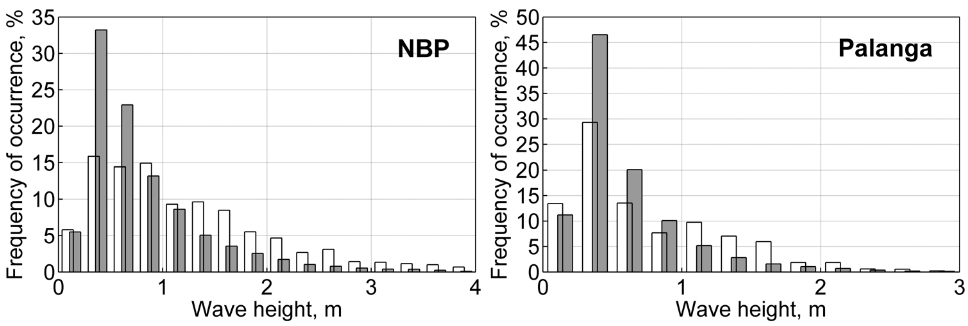

Figure 11. Frequency of occurrence of wave heights in the northern Baltic Proper (NBP) in 1996–2000 (white bars: observations, Kahma et al., 2003; grey bars: WAM model) and at Palanga in 1993–2005 (white bars: observations, Kelpšaite et al., 2008; grey bars: WAM model)

Surprisingly, the model gives one of the best matches with observations at Pakri. As the measurements there ceased in 1985, wave properties from different time intervals are presented in Figure 12. Only the frequency of 0.25–0.5 m high waves is overestimated by the model. The match is less satisfactory at Narva-Jõesuu where very low waves ($H_S < 0.25$ m) form almost half the observed data but are not captured by the model (Figure 12). These features are not unexpected at Narva-Jõesuu where the predominant south-western winds are blowing off the land and low waves are frequently observed even under relatively high wind speeds. The same situation may also occur at times at Pakri where there is a relatively large deep sea area in the south-western direction.

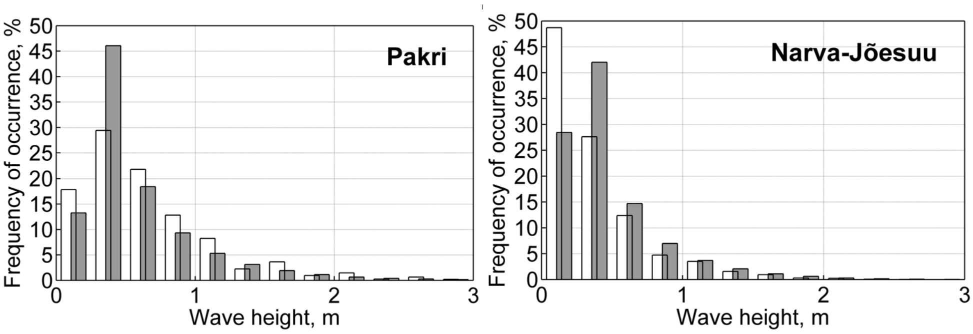

Figure 12. Frequency of occurrence of wave heights at Pakri (white bars: observations 1954–1985, Zaitseva-Pärnaste, 2009; grey bars: WAM model 1970–2007) and Narva-Jõesuu in 1970–2007 (white bars: observations, Zaitseva-Pärnaste, 2009; grey bars: WAM model)

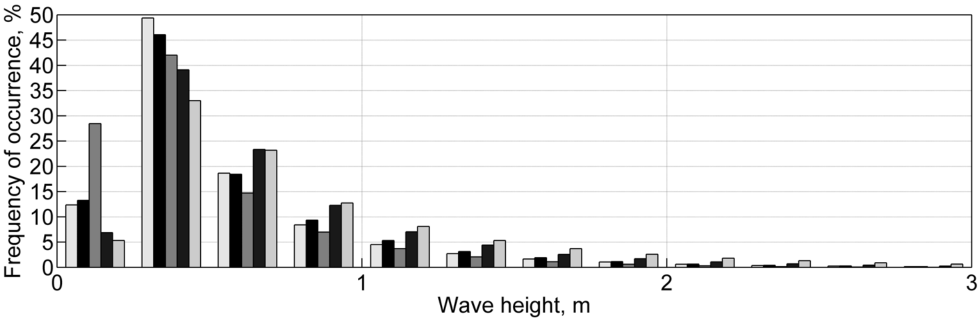

Figure 13. Numerically simulated frequency of occurrence of wave heights for 1970–2007, bars from the left: Vilsandi, Pakri, Narva-Jõesuu, Almagrundet, NBP

Another reason for the frequent presence of low waves and the mismatch between the modelled and observed data is the sea-breeze that is well developed in north-eastern Estonia over the summer season and occasionally also in autumn (when it is driven by the temperature difference between the cold land and the warm sea). As the wind turns over the day under seabreeze conditions, the wave height is to some extent affected by this phenomenon that may locally create larger waves than weak geostrophic wind in remote sea areas. Also, ice conditions frequently impact the sea state at this site (Sooäär and Jaagus, 2007). The match of the modelled and observed data for all waves with heights <0.5 m is, however, good, as it is for the distribution of higher waves.

The overall shape of the numerically simulated PDFs of the occurrence of different wave heights varies in different places, mirroring the relative openness of the sea areas (Figure 13). The smallest fraction of low waves occurs in the central northern Baltic Proper. Larger fractions of low waves are evident in coastal areas at Pakri and Vilsandi and the largest at Narva-Jõesuu. Conversely, the fraction of large waves is the highest on the open sea. A "threshold" separating the different content of waves in these distributions is at the wave height of about 0.75 m, which roughly corresponds to the long-term mean wave height in open sea areas (Table 1).

The mismatch between the modelled and observed wave properties is the largest for low wave heights ($H_S < 0.25$ m). Accurate modelling and measurement of such waves is a challenge and the results are frequently very sensitive with respect to the particular procedure. Many mismatches probably stem from the inaccuracies of wind data. For example, the HIRLAM model often underestimates the wind speed (Jönsson, 2005). The MESAN data also tend to underestimate the winds (Häggmark et al., 2000). The analysis in Section 2.5 suggests that adjusted geostrophic wind data lead to about the same accuracy of the reproduction of different wave conditions.

Another intrinsic reason for the discrepancy between the observed and hindcast wave data is that the visual observation points are located much closer to the coast than the relevant centres of the grid cells. Therefore it is safe to say that the model in use satisfactorily replicates the basic long-term properties of wave fields and also the empirical probability distributions of different wave heights.

3.3. Wave fields in extreme storms

The empirical probability distributions of the frequency of occurrence of different wave heights and periods have been thoroughly discussed in earlier studies (Kahma et al., 2003; Broman et al., 2006; Soomere and Zaitseva, 2007; Soomere, 2008; Zaitseva et al., 2009). 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.

A somewhat unexpected feature is that the observed data set for Narva-Jõesuu contains a larger proportion of waves with periods of 3–4 s than the data for Pakri or Vilsandi. A probable reason for such a large content of longer waves is that frequent westerly winds (that have quite a large fetch, >150 km) may bring to Narva Bay appreciable quantities of remotely generated wave energy, optionally stemming even from the northern Baltic Proper (Paper IV).

The combinations of wave heights and periods in the roughest storms can be estimated from the empirical 2D distributions of the joint probability of occurrence of wave conditions with different heights and periods (Figures 14 and 15). Such distributions are at times also called scatter diagrams of wave heights and periods (Kahma et al., 2003). The empirical probability distributions of the frequency of occurrence of different wave heights and periods can be obtained from these 2D distributions by integration over the relevant direction.

The most typical combinations of wave properties apparently correspond to points located at the "crests" of this distribution that is interpreted as a surface elevation map of probabilities. The possibilities for a consistent definition of these crests are discussed in Paper III. 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 spectrum (Figure 14). Notice that similar diagrams for the open ocean usually represent a superposition of two such elevations. One of them corresponds to windseas, whereas the other one represents swells with relatively large periods and moderate or low heights. The latter branch is almost degenerate in the Baltic Proper where it becomes evident as a pool of waves with periods of 8–12 s and heights up to 0.5 m (Figure 14, Almagrundet, measurements).

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 Pierson–Moskowitz spectrum: such conditions correspond to high and short, thus very steep waves that are frequently connected with acute danger to ships (Toffoli et al., 2005).

The instrumental data from Almagrundet (Figure 14) and Bogskär in the north-eastern part of the Baltic Proper and from a directional waverider (Figure 2) in the central part of the northern Baltic Proper (Kahma et al., 2003; Soomere, 2008) show that the roughest seas in the Baltic Sea 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 northern Baltic Proper (Soomere, 2008).

The scatter diagrams for the observed and modelled waves are similar at all observation sites for low and moderate wave conditions, up to wave heights of 3 m (Figures 14 and 15). For all sites, 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 more sheltered locations of these sites where swells may frequently dominate.

The distributions of numerically simulated wave conditions are narrower. This is an expected feature and probably reflects the relatively large uncertainty in visual detection of the wave properties. Another source of differences is the finite resolution of the wave model: the observation site and the nearest grid point for which the wave properties are calculated usually do not coincide.

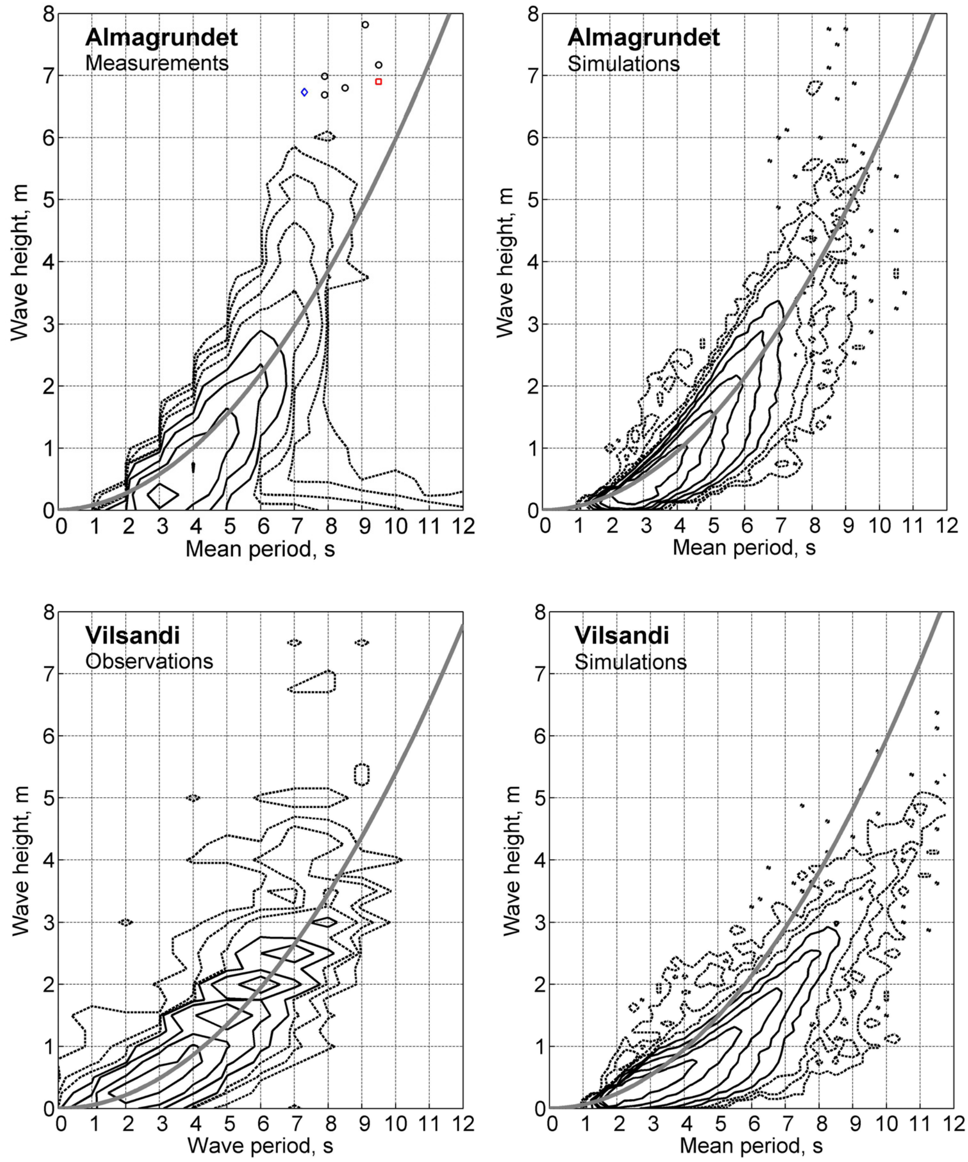

Figure 14. Joint distribution of the measured or observed (left column, all sensible wave observations with a non-zero wave period at Almagrundet (1978–1995; Soomere, 2008) and Vilsandi (1954–1994)) and modelled (right column, 1970–2007) wave heights and periods. The wave height step is 0.25 m for the observed and 0.125 m for the 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 Pierson–Moskowitz spectrum for the given mean or peak period

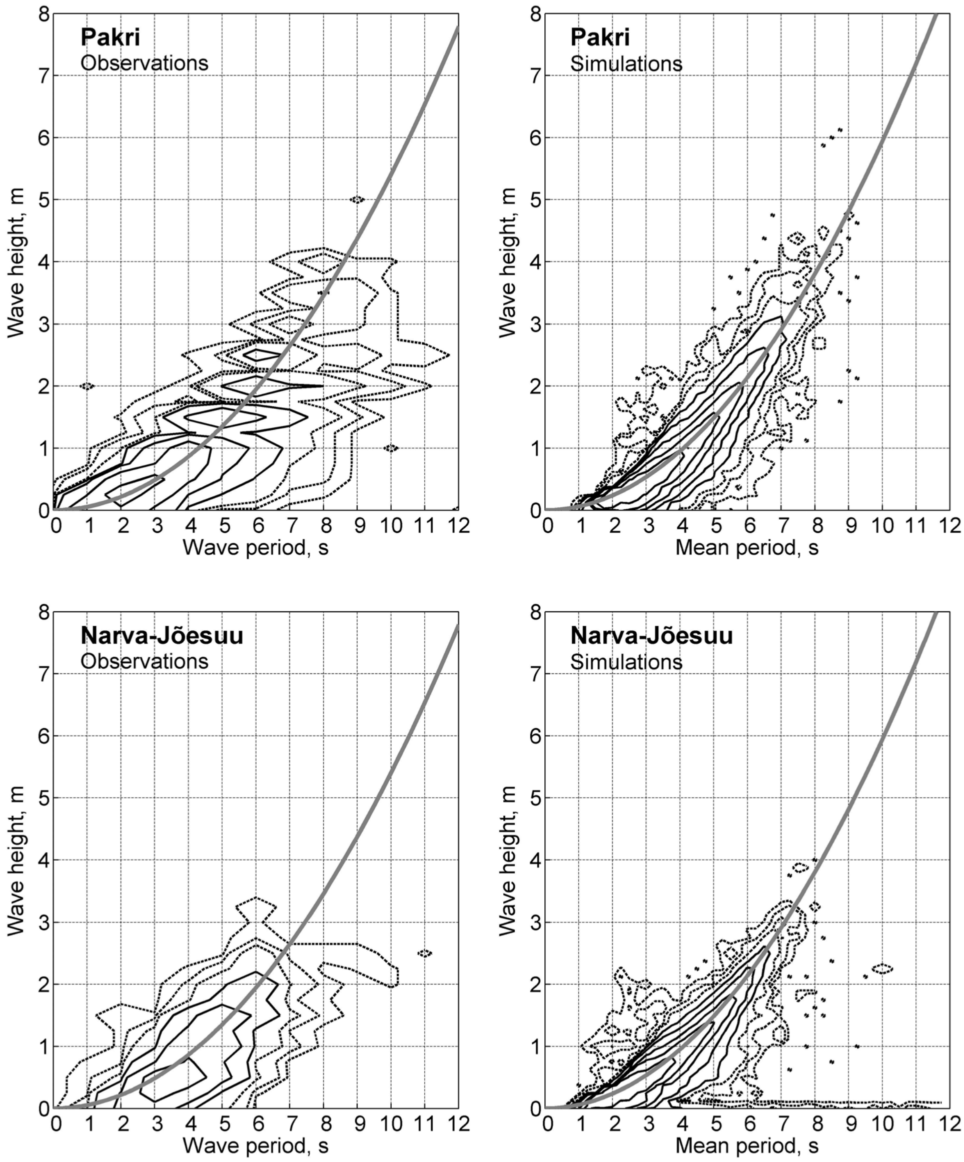

Figure 15. Joint distribution of the observed (left column, all sensible wave observations with a non-zero wave period at Pakri (1954−1985) and Narva-Jõesuu (1954−1974)) and modelled (right column, 1970–2007) wave heights and periods. The wave height step is 0.25 m for the observed and 0.125 m for the 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 Pierson–Moskowitz spectrum for the given mean or peak period

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 properties of wave fields with the Pierson–Moskowitz spectrum at Narva-Jõesuu.

The largest difference in the shape of the distributions in question is at Vilsandi where, 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 are already breaking 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 once in about 40 years may slightly exceed 6 m at Vilsandi and 5 m Pakri. Notice that the observed wave heights of 7−8 m at Vilsandi are obviously overestimated (Soomere and Zaitseva, 2007). The corresponding mean wave periods are 11−12 s at Vilsandi but much smaller, about 9−10 s at Pakri. The difference in 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 that 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 smaller than at Vilsandi.

The described overall match of the shape and basic properties of the analysed joint distributions of wave heights and periods additionally confirms that the wave model in question properly reproduces the long-term statistics of wave fields in the north-eastern Baltic Sea. This conclusion motivates its use for the analysis of the temporal variations in the wave properties in severe storms as described in Paper III and below in Section 4.4.

3.4. Seasonal variability

Jönsson et al. (2002) demonstrated great seasonal variability of the monthly mean and maximum wave heights over the Baltic Sea. This is caused by a substantial seasonal variation in the wind speed in this basin (Mietus, 1998), which is accompanied by variations in the angular distributions of wind speeds 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 mildest months are in late spring and early summer (Figure 16). The variations in the monthly mean wind speed are about 60%: for example at Utö (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.

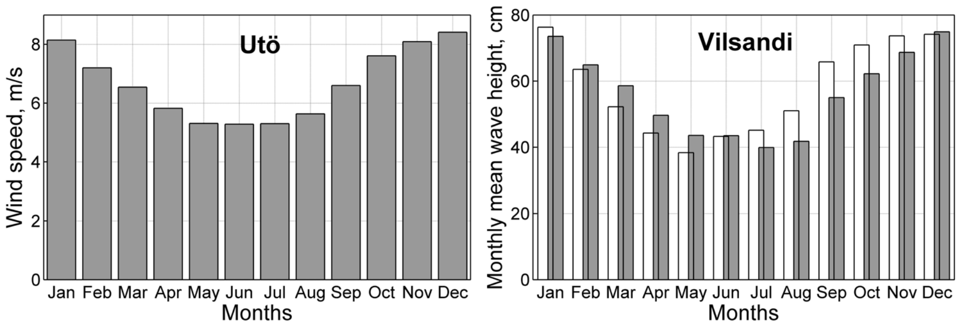

Figure 16. Seasonal variation in the monthly mean wind speed at Utö (1961–2001) and in the monthly mean wave height at Vilsandi (white bars: observations 1954–2008, Zaitseva-Pärnaste, 2009; grey bars: WAM model 1970–2007)

As a first step towards the quantification of the seasonal variability in wave properties in the Baltic Sea, we compare the modelled, and observed or measured data. Seasonal variation in the monthly mean wave heights is clearly evident in wave fields recorded in the coastal areas of Estonia (Figure 16). Wave intensity largely follows the seasonal pattern in the mean wind speed and is the highest in late autumn and early winter (December–January) and the smallest in late spring and summer (Soomere and Zaitseva, 2007; Zaitseva-Pärnaste et al., 2009). This variation is generally adequately reproduced in numerical simulations of wave conditions (Jönsson et al., 2002; Suursaar and Kullas, 2009; Paper I).

The relative amplitude of the variation in the monthly mean wave height is somewhat larger than the similar variation in the wind speed: from about 0.39 m (0.40 m as simulated) in the calmest months to 0.77 m (0.75 m as simulated) in the windiest months at Vilsandi (Figure 16). To a certain extent this feature can be explained by the frequent presence of weak wave fields in near-coastal areas, where relatively low waves are observed even in case of quite strong but offshore winds, as discussed above for Narva-Jõesuu (Figure 12). However, seasonal variations in wave heights at sites reflecting well the properties of open sea waves (such as Vilsandi or Pakri) should be clearly more pronounced than the variations in wind speeds, because in many conditions (for example, fully developed wave systems) wave heights are proportional to the wind speed squared. This feature is to some extent consistent with the fact that in many cases the Baltic Sea wave systems are steeper than fully developed wave fields with the same wave height or period (Soomere, 2008; see also analysis below and in Paper III).

Seasonal variations in the wave height at different offshore sites in the Baltic Proper follow almost perfectly also the variations in the wind speed at Utö. The relative amplitude of the variation is almost the same from the southern part of the Baltic Sea up to the entrance to the Gulf of Finland.

However, seasonal variation in the measured and observed wave intensity somewhat deviates from the pattern of the wind speed in coastal areas of Estonia (Figure 17) and Sweden (Figure 18). The data from the Gulf of Finland reveal a secondary maximum in wave intensity in October, which is the overall maximum at Narva-Jõesuu. This feature is not evident at other sites (although relatively high wave activity in October can also be seen in the observed data from Vilsandi in Figure 16) and thus can be attributed to the wave climate of the south-eastern coast of the Gulf of Finland. The occurrence of relatively high waves compared to the monthly mean wind speed in early autumn (September–October) seems to be an overall feature of the wave climate in the north-western coastal waters of Estonia. As it is much less clearly expressed starting from about 1980, it may partially be caused by the regular presence of the ice cover.

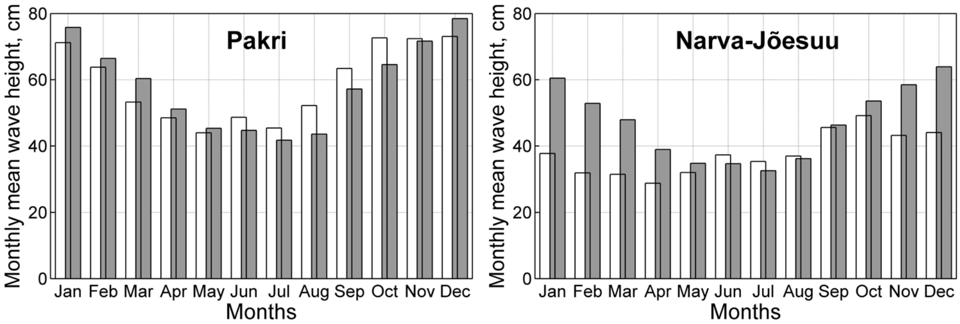

Figure 17. Seasonal variation in the monthly mean wave height at Pakri (white bars: observations in 1954–1985, Zaitseva-Pärnaste, 2009; grey bars: WAM model 1970–2007) and Narva-Jõesuu (white bars: observations 1954–2008, Zaitseva-Pärnaste, 2009; grey bars: WAM model 1970–2007)

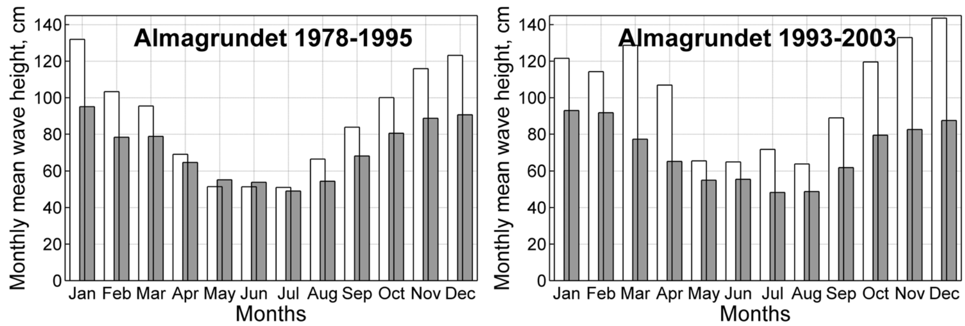

Figure 18. Seasonal variation in the monthly mean wave height at Almagrundet in 1978–1995 and in 1993–2003. White bars represent measured (Broman et al., 2006) and grey bars – modelled wave heights

Another interesting feature is a minor maximum in the observed wave heights at Pakri in June. It is not explicit at Vilsandi but can still be traced as a relatively high monthly mean wave height compared to that in May. The inability of the model to reproduce this feature suggests that it is caused by local ageostrophic wind properties. The wind field in the Gulf of Finland contains at times (especially in spring and early summer; Mietus, 1998) quite strong eastern and western winds blowing along the axis of the gulf (Soomere and Keevallik, 2003), which is specific to this water body.

The rather large discrepancy between the measured and hindcast wave heights at Almagrundet (Table 1) is mostly caused by systematic overestimation of wave heights by the measurement devices during relatively windy months (Figure 18). The measured and modelled wave heights almost coincide during the calmest months (May–July), especially in 1978–1995.

The wave intensity in March (and sometimes in April) was systematically higher than in February and even in October in 1993–2003 at Almagrundet. This peculiarity is not recorded at other sites in the central and eastern parts of the Baltic Sea. One reason for this may be measurement noise, as discussed above. It may, however, be connected with the impact of easterly winds in years with a moderate ice cover. Although such winds are generally relatively infrequent and weak in the northern sectors of the Baltic Sea (Mietus, 1998; Soomere and Keevallik, 2001), they may at times extend from the Gulf of Finland (Soomere and Keevallik, 2003) to the northern Baltic Proper. Note that the roughest wave conditions recorded in the northern Baltic Sea were measured at Almagrundet during an extreme eastern storm in 1984 (Broman et al., 2006).

3.5. Stormy and calm seasons

The above analysis reveals that during the first half of the year the model overestimates, and during the second half underestimates the monthly mean wave heights at several wave observation sites (Figures 16 and 17). This peculiarity suggests that a phase shift (time lag, about one to two months) may occur between the seasonal course of the wind speed and wave heights (and even more between the observed and modelled wave heights, Figure 17) in the coastal areas of Estonia (Paper II). In other words, the windiest season does not necessarily coincide with the season with the largest wave activity in the Baltic Sea. The physical reasons behind this feature are to some extent discussed in Paper II but are still unclear.

The time lag can roughly be estimated by means of separating the stormy and calm half-years. The five-month period from April to August is generally the calm time and five months from October to February are windy (Figure 16). The other two months serve as transient periods and may belong to either of the seasons.

At Utö the windy and calm half-years are most clearly distinguished when September is allocated to the windy season and March to the calm season (Figure 19). The average wind speed in the calm and windy seasons is 5.5 m/s and 8 m/s, respectively. Figure 19 also shows that the wind speed (in total about 2.5% annually) has increased at a more or less uniform rate of about 2% in March–November but much faster, about 3.5% annually during the second half of the windy half-year (December–February).

A similar distinction of rough and calm seasons in terms of the monthly mean wave height is presented in Figure 19 for the modelled wave heights. An attempt to separate the half-year of rough seas starting from September does not lead to a satisfactory result, as the wave intensity during the spring and autumn seasons differs insignificantly. On the other hand, wave conditions are, on average, clearly rougher during October–March (average about 0.7 m at Vilsandi) than in April–September when the average wave height is about 0.45 m.

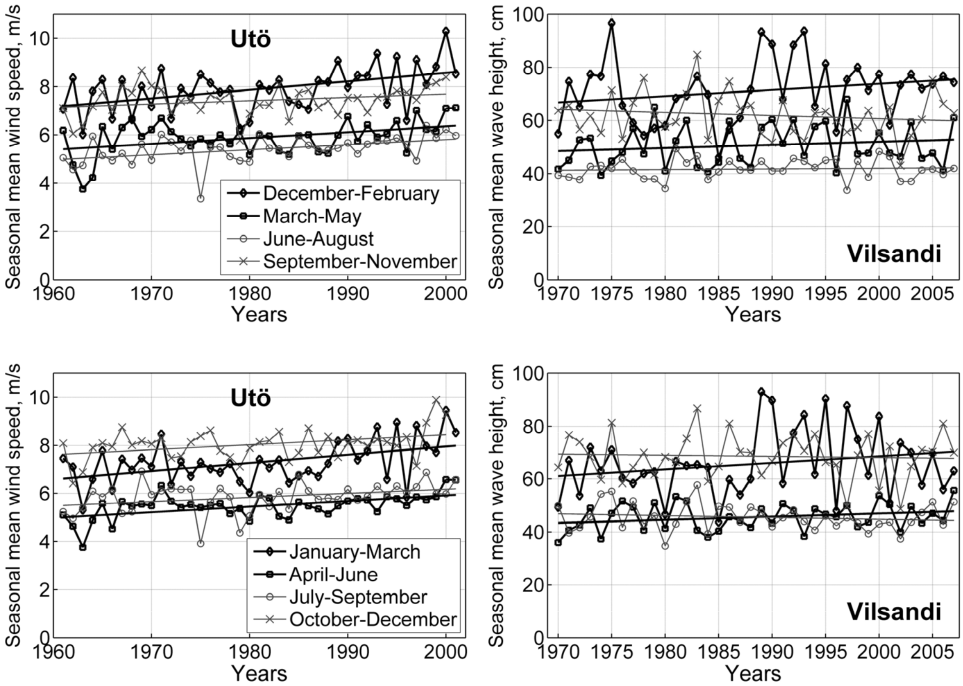

Figure 19. Long-term trends in wind speed and the modelled wave height in the windy and calm seasons at Utö and Vilsandi for different separation dates (1 September or 1 October) between windy/relatively rough and calm seasons

An attempt to construct a more exact estimate of the time lag between the overall patterns of seasonal variation in wind and wave conditions has been made in Paper II by approximating the relevant variation with the following periodic function:

$$f = \alpha \cos(2\pi t/12 + \beta) + \gamma \,, \qquad (3)$$

where α expresses the amplitude of the annual variation in the property in question (wind speed or wave height), γ characterizes its annual average value and β is the shift of its maximum from the beginning of the year. The parameters of the best approximation can be determined, for example, in terms of the minimum root-mean-square deviation of the values of $f(\alpha, \beta, \gamma, t_i)$ from the relevant observed or modelled monthly mean values. Here t_i, $i = 1,...,12$, are associated with the numbers of the relevant months.

The first approximations of the parameters α and γ are the total range of annual variation in the monthly means and the average annual value of the relevant property, respectively. The difference in the parameter β for different properties characterizes the time lag between their seasonal patterns. It is about half a month for the wind speed at Utö and the observed wave heights at Vilsandi, almost a month for the observed and modelled wave heights at Vilsandi and about two months for the observed and modelled wave heights at Pakri (Paper II).

The discrepancy between the match of the temporal pattern of the wind speed and wave heights may have its origin, for example, in gradual changes in the predominant wind direction, intensity, trajectory, or in the persistence of storms. During the period in question, the frequency of south-western winds has increased almost twofold at the expense of eastern and southern winds (Kull, 2005). This change may cause an increase in wave heights in the entire northern Baltic Proper (Broman et al. 2006; Soomere and Zaitseva, 2007) but has almost no impact on wave fields in fetch-limited conditions in the bays of northern Estonia and in the south-eastern Baltic Sea (Kelpšaite et al., 2008, 2009).

Finally, simulations performed with the use of adjusted geostrophic winds do not reveal any substantial long-term intensification in wave activity, although the measured 10 m level wind speed has gradually increased over this time. An increase in wave heights only becomes evident for early winter (December–February; Figure 19), whereas during all other seasons almost no changes have taken place in wave intensity.

4. Wave climate changes

4.1. Introduction

Studies of properties of complex wave fields in different sea areas and research towards the understanding of both the status of and changes in the wave climate undoubtedly 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 sensitive indicators of the 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 larger than that of the wind speed (7% for the 99%-ile; Grabemann and Weisse, 2008). An accurate picture of typical and extreme wave properties is obviously necessary for a wide variety of research topics and coastal engineering applications. Changes in 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., 2010).

Research into long-term changes in wind properties and storm activity over the Baltic Sea has highlighted greatly variable patterns of changes (Jaagus et al., 2008). The average wind speed over most of this basin (especially in its southern part) increases (Pryor and Barthelmie, 2003), while a decrease occurs in a part of the Western 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). A considerable increase in the number of storm days at Vilsandi even raised 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 has decreased since the mid-1990s (Alexandersson et al., 2000; Helminen, 2006).

The combination of significant wind anisotropy and seasonal variation in the wind speed gives rise to high anisotropy and large spatio-temporal variations in the Baltic Sea wave fields (Jönsson et al., 2002; Soomere, 2003; Broman et al., 2006; Kelpšaite et al., 2008). The areas with the largest average wave intensity are apparently formed under relatively high mean wind speeds and large fetch in the southern and north-eastern regions of the Baltic Sea (Jönsson et al., 2002). The monthly maximum wave heights occur in the northernmost and southernmost coastal regions of this water body. Waves may be extremely high also offshore the coasts of Latvia and Saaremaa (Jönsson et al., 2002; Soomere et al., 2008). Several related characteristics such as hydrodynamic bottom stress and resuspension patterns are strongly correlated with the features of the wave climate listed above (Elken et al., 2002; Jönsson et al., 2005).

This chapter focuses on several key features of the long-term changes in wave fields and mostly follows the material presented in Papers III and IV. I start from the comparison of interannual and decadal changes in the annual mean wave height extracted from visually observed and instrumentally measured wave data with the similar characteristics derived from numerical simulations. To a first approximation, these features are studied on the basis of single calendar years in Section 4.2. As each year may contain two seasons of high waves, I shortly address the potential variations in the above features calculated for time intervals from July to June of the subsequent year in Section 4.3.

Equally important properties of wave climate are the level of and the changes in the wave conditions in strong storms (Section 4.4). These features are studied considering the long-term variations in the thresholds for 5% and 1% of the highest waves in each calendar year (called the 95%-ile and 99%-ile, respectively). As the relevant estimates based on visual observations are less reliable than the above estimates of changes in the annual mean wave height, the analysis is performed only for numerically simulated wave fields. Finally, the potential changes in wave periods and directions (Section 4.5) are addressed. While substantial changes in periods are hardly possible in the Baltic Sea basin, variations in directional distributions of wave fields may affect the evolution of sedimentary coasts.

4.2. Long-term trends in significant wave height

The study of long-term variations in wave conditions is based on three time series of wave observations, the data from Almagrundet and numerically simulated time series. I start the discussion with the analysis of the annual mean wave heights, obtained directly from the daily mean values of wave conditions observed during a calendar year (Figure 20). In order to understand the role of gaps in the observed data, I consider the analogous time series in which the missing measurements have been replaced by their climatological values for the same calendar day.

The reason behind 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 a high wave intensity at Vilsandi in 1954–1956 may be real. Still, I omit these years as doubtful data in the correlation analysis below.

All four time series of the annual mean wave heights based on visual observations show a reasonable match of years of relatively high and low wave intensity at all measurement sites in 1957–1986 (Figure 20, Table 4). Accordingly, there is a high correlation between annual mean wave heights at all sites in 1957–1986. The correlation coefficients range 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 Sea coast from the Baltic Proper to Narva Bay in these years.

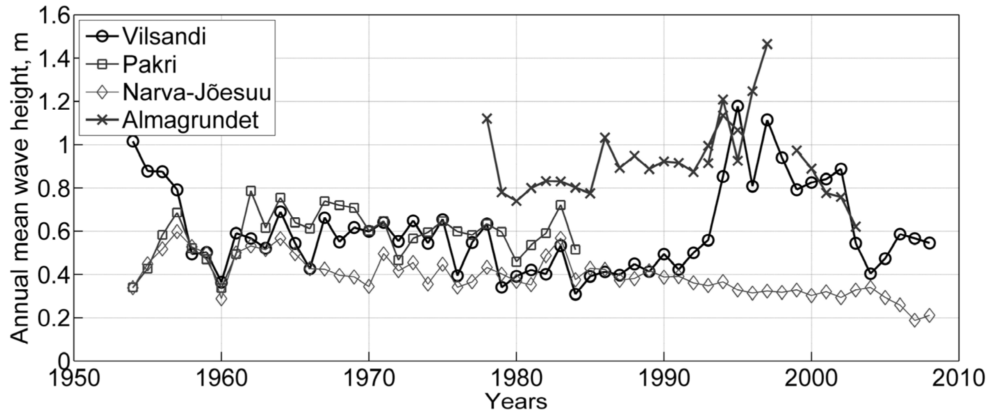

Figure 20. Long-term variations in wave heights at Vilsandi, Pakri, Narva-Jõesuu and Almagrundet

Interestingly, this coherence in the long-term variation in wave heights ends abruptly at the end of the 1980s (Figure 20, Table 4). While the wave activity reveals drastic decadal-scale increase and decrease in the Baltic Proper during the 1990s and 2000s, a gradual decrease in the annual mean wave height (0.4% per annum) was observed at Narva-Jõesuu. Since the 1980s, years with relatively high wave intensity at Vilsandi correspond to relatively calm years in Narva Bay.

This change is vividly expressed in terms of correlations between the annual mean wave heights observed at different locations (Table 4). From Figure 20 it follows that the coherence is abruptly lost starting from the year 1987; for this reason I 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 at all.

Table 4. 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 and 1987–2008 for Vilsandi and Narva-Jõesuu); the lower left cells show the relevant p-values (in italic)

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

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) afterwards (Table 5).

This feature becomes even clearer when the missing observations are replaced by the climatological mean values (see below).

Table 5. Correlation coefficients (r), biases (in cm) and standard deviations (STD, in cm) between numerically simulated and observed time series of the annual mean wave heights at Vilsandi, Pakri and Narva-Jõesuu

Vilsandi	Uncorrected data			Climatologically corrected data		
Time period	Correlation	Bias	STD	Correlation	Bias	STD
1970–2007	r = 0.13	2.8	21.3	r = 0.32	13.4	16.3
1970–1988	r = 0.34	6.5	12.5	r = 0.53	10.5	12.0
1988–2007	r = 0.16	11.0	27.2	r = 0.06	16.0	19.7

Pakri	Uncorrected data			Climatologically corrected data		
Time period	Correlation	Bias	STD	Correlation	Bias	STD
1970–1984	r = 0.64	1.3	5.3	r = 0.64	1.6	4.8

Narva-Jõesuu	Uncorrected data			Climatologically corrected data		
Time period	Correlation	Bias	STD	Correlation	Bias	STD
1970–2007	r = 0.36	9.7	11.8	r = 0.32	8.8	10.3
1970–1985	r = 0.74	4.5	6.1	r = 0.69	5.8	6.9
1985–2007	r = 0.15	12.9	14.4	r = 0.03	10.6	12.1

The described features indicate that certain substantial changes in wind properties have apparently occurred over the Baltic Sea since the mid-1980s. These changes, if real, have led to an increase in the wave intensity in areas open to southerly winds. However, almost no changes in wave intensity have taken place in regions affected by waves approaching from the northern and western directions (cf. Kelpšaite et al., 2009). Further, the described variations in the overall wave activity have occurred on the background of gradually increasing wind speeds in the Baltic Proper (Broman et al., 2006; Pryor and Barthelmie, 2003, 2010). Consequently, such changes have mostly been caused by southern and south-western winds.

This conjecture matches the results of the analysis by Kull (2005) who shows that during the last 40 years there has been a significant increase in the frequency of south-western 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 northern Baltic Proper 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 in Narva Bay.

Simulations show that during the last 38 years the wave intensity has decreased in the western part and increased in the eastern part of the Baltic Sea (Figure 21). In the Gulf of Finland and in the north-eastern part of the Baltic Proper there have been almost no changes in wave heights. A great increase in wave activity in the Arkona basin was expected because according to recent wind climate studies, wind speeds in this area have substantially increased (Pryor and Barthelmie, 2003).

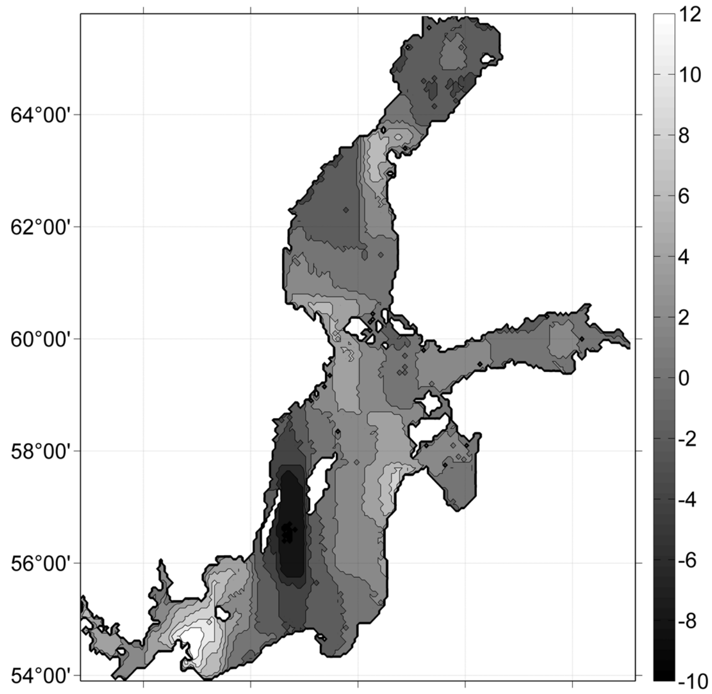

Figure 21. Long-term changes in significant wave height (brightness scale, cm; isolines plotted after each 2 cm) in the Baltic Sea in 1970–2007

Climatologically corrected variations in wave heights

As discussed in Paper IV, the observed wave data from Vilsandi contain extensive gaps (see also Soomere and Zaitseva, 2007) that may to some extent affect the conclusions derived from the analysis of this data set. These gaps may result, for example, from the presence of ice cover in the vicinity of the observation site. Moreover, data are lacking for July–September 1990 and no wave observations were performed in August–December 1997. Also, the average number of days with ice has decreased steeply in the entire Western Estonian Achipelago (Jaagus, 2006). As the annual mean wave heights have been calculated on the basis of the average wave heights only over the days when at least one sensible wave observation was performed, the absence of data from relatively calm periods eventually leads to an overestimation of the annual mean wave height. Similarly, lack of wave data from a windy season generally causes an underestimation of the annual mean wave activity.

The impact of the gradual lengthening of the ice-free season may be complicated. The ice has covered the coasts of Hiiumaa and Saaremaa islands from mid-November to mid-April in the past. The changes in the start and end of the ice season have been almost symmetric, 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 increase 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 in the length of the ice-free season). Therefore, the correlation between the annual mean wave intensity and the length of the ice season is mostly implicit.

In order to eliminate part of potential distortions caused by missing data, the recorded time series of wave heights were amended with the use of the climatological mean values of wave intensity for each calendar day. Such a "climatological correction" introduces a certain amount of noise because of the character of seasonal variations in the daily mean wave height (Paper IV). The described method, however, avoids the bias connected with a more regular presence or the absence of measurements in transitional months such as April and with possible 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.

The annual mean wave heights obtained from the observed time series and from the climatologically corrected time series almost coincide for most of the data at Pakri and Narva-Jõesuu (except for a few most recent years, Figure 22). A certain divergence of these values is noted at Vilsandi between 1970 and 1990, whereas the climatologically corrected values are somewhat larger. This feature is apparently due to relatively high observed wave activity at the turn of the millennium. As expected, the annual mean wave height for the climatologically corrected time series is clearly smaller than that for the original data for extremely stormy years of 1995 and 1997 (Figure 22). Also, the wave intensity in relatively calm years, especially in the 1980s, increases considerably when the winter data follow the climatological mean values. The best estimate for the actual wave intensity evidently lies between the two values.

The climatological correction leads to a substantial increase in the correlation between simulated and observed annual mean wave heights (Table 5), 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. Surprisingly, the correlation between the simulated and observed values of the annual mean wave heights is completely lost for the years 1988–2007.

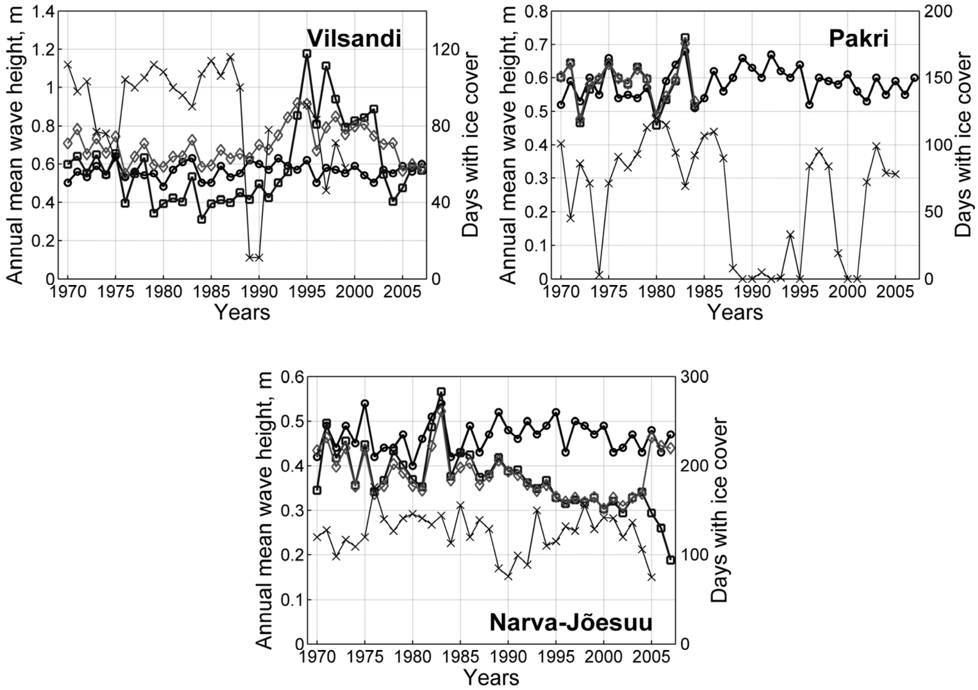

Figure 22. Long-term variations in wave heights at Vilsandi, Pakri and Narva-Jõesuu. The original observed time series is shown by squares, climatologically corrected time series by diamonds, numerically simulated time series by circles and the duration of ice coverage by crosses (estimated as the number of days from the first appearance of ice to the total disappearance of ice)

The differences between the course of the annual mean wave heights obtained from the observed data and from climatologically corrected time series are relatively large (up to 30% of the relevant values) for Vilsandi. As expected, the climatologically corrected mean wave heights are greater for years with 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 1990s and at the turn of the millennium. The increase in the overall wave intensity at the beginning of the 1990s is smoother, but there is still evidence of substantial increase in the wave heights in 1993–2002 compared with the long-term mean.

The original and climatologically corrected values of the mean wave heights differ much less for Pakri and Narva-Jõesuu. The largest difference becomes evident for Narva-Jõesuu starting from 2005. The original and corrected values almost exactly coincide for Vilsandi for these years.

Surprisingly, filling the gaps with climatological values causes quite substantial increase in the differences 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 increased to 13.4 cm for the amended data (Table 5). The difference was the largest for the years 1988–2007 for which the match of the observed and measured data was the worst. This feature could be interpreted as an evidence that the forcing in use results in an overall slight underestimation of wave heights in the Baltic Proper.

4.3. Wave heights over stormy and ice seasons

In the above discussion the time series of the annual mean wave heights were calculated over two relatively windy time periods: 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 year. A time series, which more adequately reflects the overall wave conditions during different stormy seasons, is the average wave height over periods covering both the entire windy season (September–March) and the season with the highest waves (they may have a time lag by up to two months, Paper II), separated by a date corresponding to one of the lowest annual wave heights. For simplicity, below I consider the average wave heights over the periods from 1 July to 30 June of the subsequent year. The listed quantities are calculated, as above, from the daily average observed wave heights.

The basic properties of long-term variations in the wave intensity at all sites are the same as revealed by the time series over calendar years (Figure 23). There is high interannual variation around the year 1960 in all data sets (not shown), a period of relatively low waves in the 1980s and a drastic increase over the 1990s at Vilsandi.

The correlations between numerically simulated and observed data are almost the same (albeit slightly lower) as for the data over calendar years for all three Estonian observation sites (Tables 5 and 6). The similar correlations for Vilsandi are almost the same for the last two decades but considerably higher for the originally observed and numerically simulated data for the entire period of simulations 1970–2007 and for climatologically corrected data for 1988/89–2006/07. This feature suggests that extensive periods of rough seas are concentrated in a few months at Vilsandi, whereas such periods may happen either in autumn or in winter. The WAM model and the forcing in use represent such periods to some extent but apparently have the 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 1972/73 at Pakri, whereas all other changes are mostly in phase in other years both at Pakri and Narva-Jõesuu (Figure 23).

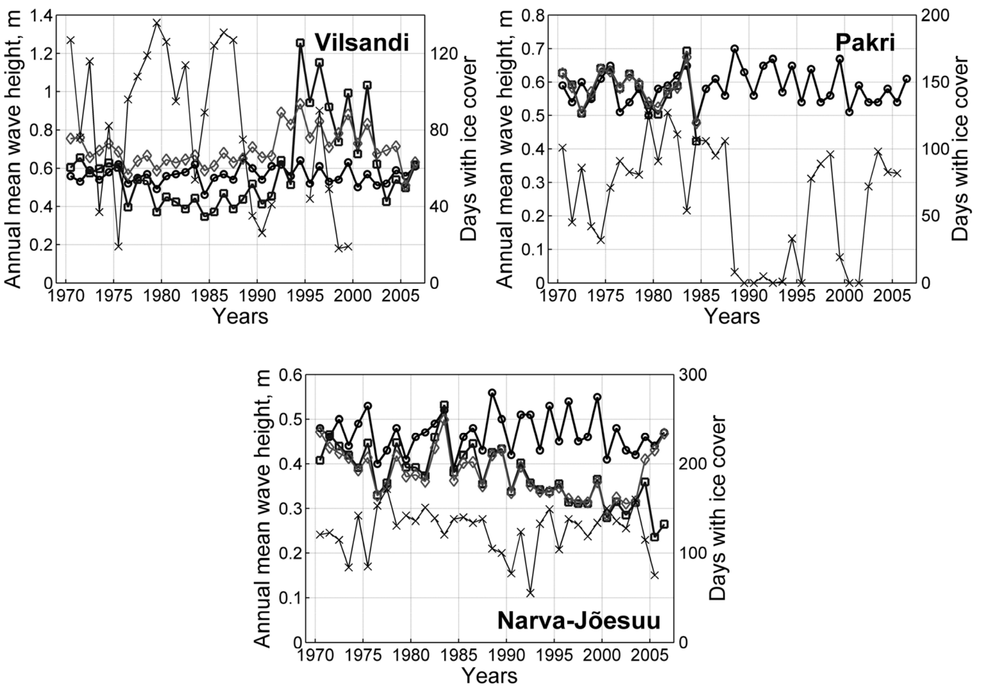

Figure 23. Long-term variations in wave heights over windy seasons (1 July–30 June of the subsequent year) at Vilsandi, Pakri and Narva-Jõesuu. The original observed time series is shown by squares, climatologically corrected time series by diamonds, numerically simulated time series by circles and the duration of ice coverage by crosses (estimated as the number of days from the first appearance of ice to the total disappearance of ice)

One of the key features forming the wave fields is the ice cover. The maximum area covered by ice in the Baltic Sea substantially varies 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 >100 days during a winter (Figure 22). The presence of ice may have twofold impact on the observed wave data. Fast ice makes wave observations impossible, leading to gaps in the time series. 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 south-western 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 in Paper IV) suggests that the absence of ice cover in 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 would lead to its decrease. A comparison of the interannual variations in the mean wave height calculated from observations and from climatologically corrected data (fig. 3 in Paper IV, Figure 22) confirms this pattern of changes. The artificial "lengthening" of the ice-free period by inserting climatological values for the missing measurements resulted in a clear increase in the annual mean wave height at Vilsandi in normal and relatively severe winters in 1975–1988.

Table 6. Correlation coefficients (*r*), biases (in cm) and standard deviations (STD, in cm) between numerically simulated and observed time series of the mean wave heights at Vilsandi, Pakri and Narva-Jõesuu, calculated for the time periods from 1 July to 30 June of the subsequent year.

Vilsandi	Uncorrected data			Climatologically corrected data		
Time period	Corre-lation	Bias	STD	Corre-lation	Bias	STD
1970/71–2006/07	$r = 0.28$	3.4	22.2	$r = 0.38$	13.5	16.2
1970/71–1988/89	$r = 0.28$	7.6	12.5	$r = 0.35$	9.6	11.3
1988/89–2006/07	$r = 0.17$	13.0	29.3	$r = 0.29$	16.7	20.0

Pakri	Uncorrected data			Climatologically corrected data		
Time period	Corre-lation	Bias	STD	Corre-lation	Bias	STD
1970/71–1984/85	$r = 0.58$	0.5	5.4	$r = 0.57$	1.0	4.7

Narva-Jõesuu	Uncorrected data			Climatologically corrected data		
Time period	Corre-lation	Bias	STD	Corre-lation	Bias	STD
1970/71–2006/07	$r = 0.38$	9.6	11.5	$r = 0.36$	9.0	10.6
1970/71–1985/86	$r = 0.66$	4.8	6.0	$r = 0.65$	6.0	7.1
1985/86–2006/07	$r = 0.43$	12.6	14.2	$r = 0.29$	11.0	12.6

In areas where the season of the highest waves (Paper II) 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 drastically intensify the coastal processes (Ryabchuk et al., 2010). These processes may be intensified by the presence of a longer fetch in coastal areas of the north-eastern 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 mild winters frequently occur simultaneously with an increase in the frequency of south-western winds (Kull, 2005). Such winds generally excite large waves neither at Pakri nor at Narva-Jõesuu.

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 the ice cover at the study sites (Figures 22 and 23). The relevant correlation coefficients are well below 0.2 and no statistically significant correlation exists.

4.4. Modelled extreme wave heights

The analysis in Section 3.3 suggests that visual observations provide no adequate data for estimates of long-term changes in extreme wave conditions. For this reason, we discuss such variations based on the simulated values of the 99%-iles and 95%-iles of significant wave height for each calendar year (Paper III). The temporal course of both percentiles (Figure 24) reveals quite large but mostly synchronous interannual and decadal variability in extreme wave conditions at all sites in question.

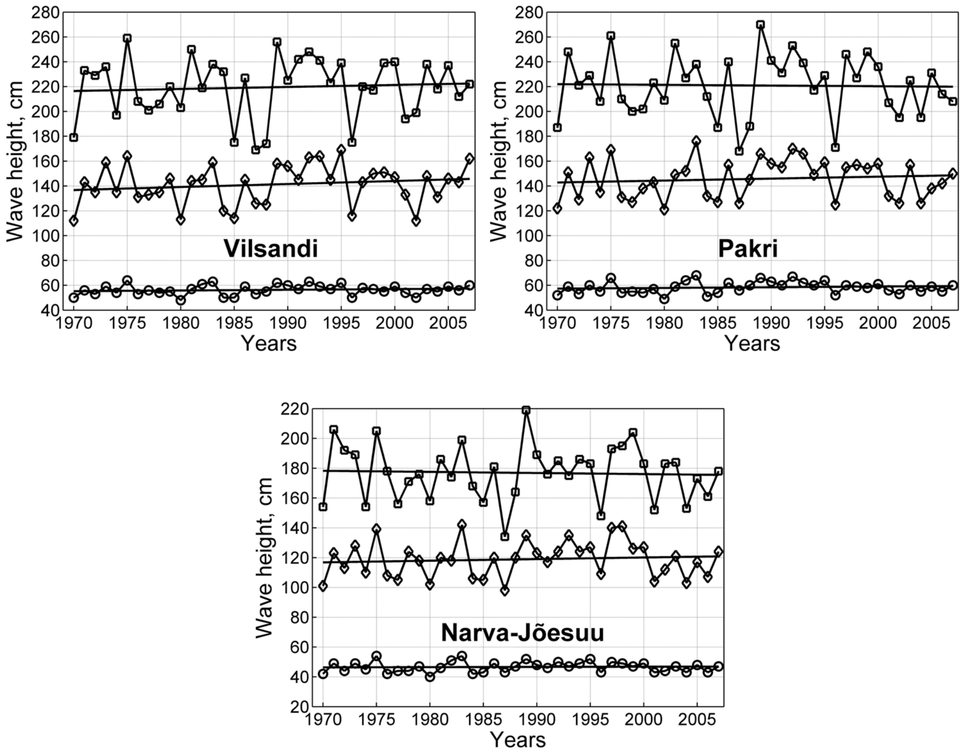

Figure 24. The annual 99%-ile (upper line) and 95%-ile (middle line) values of the significant wave height and the annual mean wave height (lower line) at Vilsandi, Pakri and Narva-Jõesuu. The straight lines show the linear trends

Relatively low extreme waves occurred in 1976–1980 and 1985–1988, whereas in 1989–1995 the extreme waves were clearly higher. The correlation coefficient between the 95%-ile and the annual mean wave height is quite high, 0.9 at Vilsandi and Pakri, and 0.84 at Narva-Jõesuu. The correlation of the 99%-iles with the 95%-iles 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 in question.

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 (Zaitseva-Pärnaste et al., 2009; Suursaar and Kullas, 2009) reveals that the short-term variability in the results of different models is basically qualitatively similar, but decadal variations are at times quite different and almost not correlated for some decades. This feature obviously stems from the better ability of the WAM model and geostrophic wind fields to reproduce the statistics of extreme events.

The analysis in Zaitseva-Pärnaste et al. (2009) and Suursaar and Kullas (2009) indicated a pronounced increase in the 99%-ile and a clear decrease in the mean wave height for the Vilsandi area. Somewhat surprisingly, the data calculated with the WAM model show no statistically significant trend of any of the percentiles. Instead, a very small increase occurs in both values simulated by the WAM model forced by geostrophic winds at Vilsandi (Figure 24). A very slight increase is recorded 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 (Paper III).

The highest waves occur in the Arkona basin, south of Gotland, in the north-eastern Baltic Proper and in the eastern Bothnian Sea (Figure 25). It is an expected outcome, having the same the reasons as those discussed earlier for the average wave heights. These areas have the longest fetch along the axis of the sea and the relatively low elevations in Denmark do not reduce winds blowing from the North Sea. Changes in extreme wave heights are almost identical to changes in average wave heights (Figure 26). Notable is the decreasing trend in 99%-iles near the north Estonian coast, which differs from trends in average wave height.

4.5. Wave periods and directions

The wave period is frequently considered as a secondary parameter of wave fields, which has often no dynamic or kinematic significance and the systematic changes in which are not easy to interpret. For example, it is obvious that establishing the maximum wave period without simultaneously considering the related wave height provides a little, if at all, useful information.

The above analysis of the 2D joint distributions of wave heights, however, suggests that wave periods (at least in strong storms) and their potential changes do play a role in the Baltic Sea. The importance of periods of predominant waves in coastal processes (for example, in terms of the parameters of the width of the equilibrium coastal profile; Dean and Dalrymple, 2002) has been generally recognized in the coastal engineering community. The potential changes in wave periods associated with changes in wave heights may thus considerably modify the course of coastal processes.

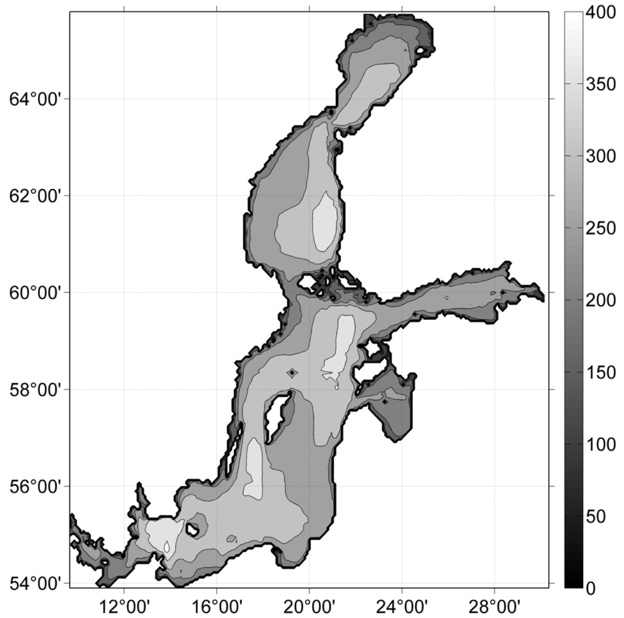

Figure 25. Long-term 99%-ile of total significant wave height (brightness scale, cm; isolines plotted after each 50 cm) in the Baltic Sea in 1970–2007

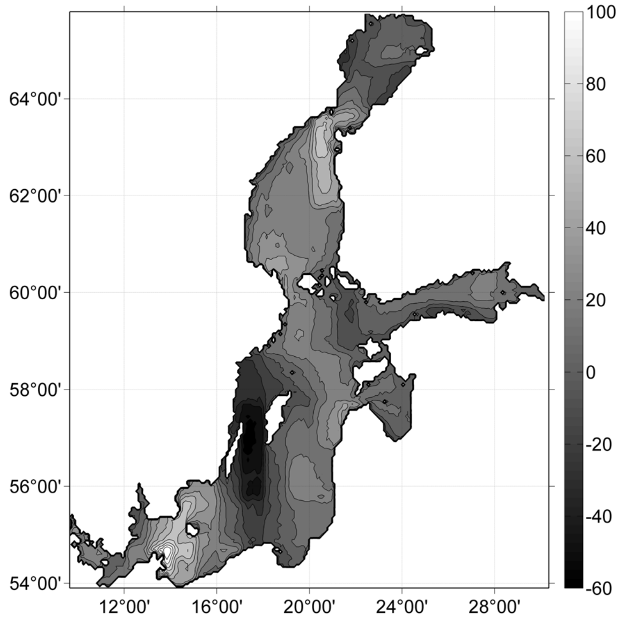

Figure 26. Linear trends in annual 99%-ile of significant wave height (brightness scale, cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007

The spatial distributions of the average values of peak periods over the 38 years of numerical simulations qualitatively match similar distributions for the wave height discussed in Section 4.2. In both cases the distributions are asymmetric in the sense that the largest values mostly occur in the eastern part of the Baltic Proper and the Bothnian Sea; yet the overall largest values occur in the southern Baltic Proper, south of Gotland.

The modelled wave periods match well the measured periods: while typical peak periods according to measurements are 4–6 s in the open sea, the average peak periods from simulations are about 4 s (Figure 27). Statistically, the longest periods, similarly to the highest waves, occur in the southern Baltic Proper. The relative variations in the average periods over the Baltic Sea basin are of the same order of magnitude as the similar variations in wave heights.

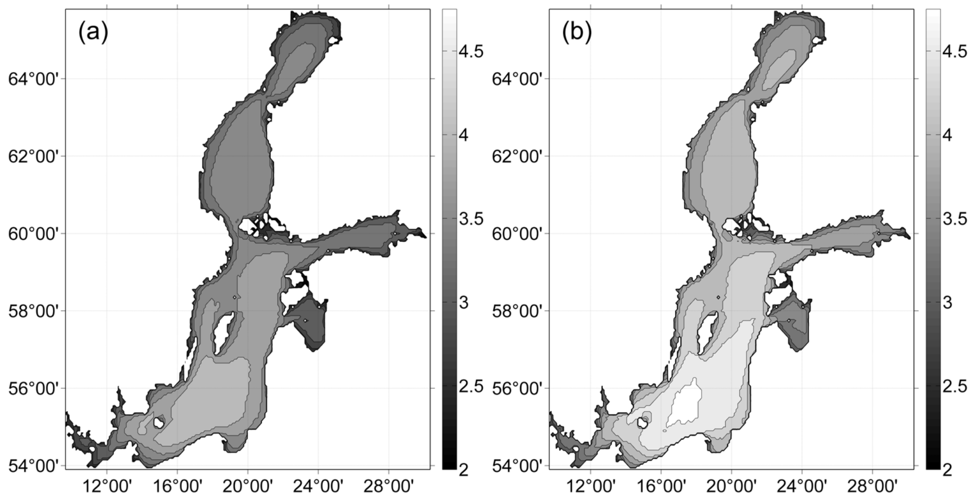

Figure 27. (a) Mean periods; (b) peak periods. The brightness scale is in seconds

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 (Figure 28). The magnitude of these changes, however, is quite small, maximally a couple of tenths of seconds and thus can be neglected in practical applications. In other words, quite substantial variations in long-term wave heights have taken place but no great increase in the typical wave periods has occurred in the Baltic Sea over the last 40 years.

Another important feature of wave fields is the propagation direction. Similarly to wave periods, this property is often dynamically insignificant but becomes decisive in specific applications such as navigation or coastal engineering. The pool of data about propagation directions is much smaller than data sets of wave heights. In this light, visual observations from the Estonian coastal waters are especially valuable as they provide historical evidence of wave directions over many decades (Paper III).

The direction of wave propagation in visual observation diaries is interpreted as the direction from which the waves approach, similarly to the definition of the wind direction. The opposite interpretation in the WAM model is reversed below, so that all figures reflect the wave approach direction.

In visual observations, the wave direction was 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 by employing other measured parameters. A few doubtful cases were left out of the analysis. The main difference here from the analysis of the observed wave heights (Soomere and Zaitseva 2007; Zaitseva et al., 2009) is that all consistent observations of wave directions up to three times a day have been accounted for.

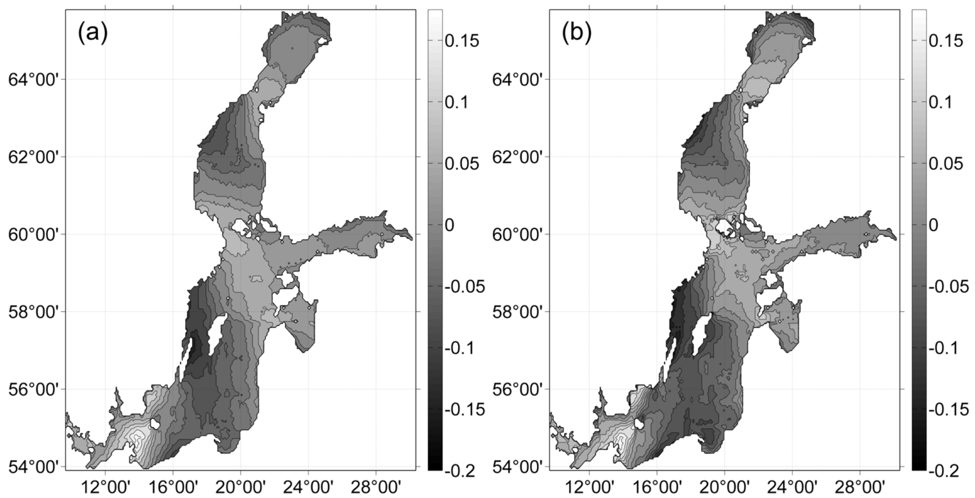

Figure 28. Changes in (a) mean periods and in (b) peak periods. The brightness scale is in seconds

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 much better than the directional resolution of the grid (15°). In order to adequately compare the observed and simulated wave propagation directions, the simulated directions are also divided into 8 rhumbs (each covering 45°) as are the visual observations.

The predominant wave directions match the directional structure of the prevailing winds and the geometry of the nearshore of the observation sites (Figure 29). 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 northern Baltic Proper where strong winds blow either from the south-west or less frequently from the north-west (Soomere and Keevallik, 2001). The observed distribution follows the same pattern. 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, whereas again the modelled and observed directions generally match each other.

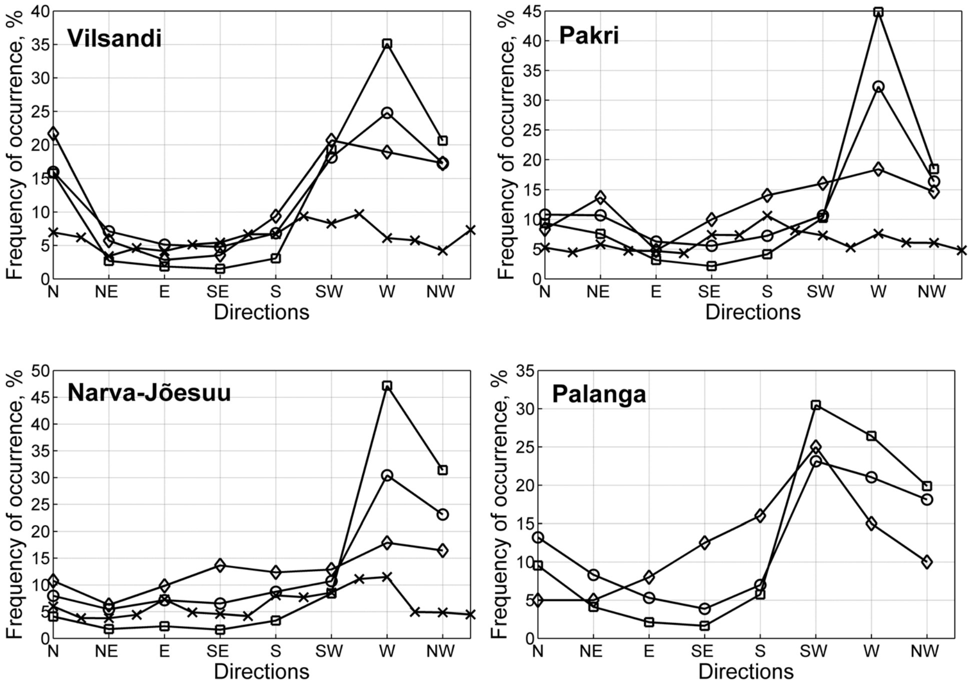

Figure 29. The distribution of the approaching directions of the observed (diamonds: all sensible observations) and modelled waves (circles: all waves, squares: waves >0.5 m) at Vilsandi, Pakri, Narva-Jõesuu and Palanga (Kelpšaite et al., 2010). Crosses indicate the distributions of winds

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 in cases of higher directional resolutions (not shown in Figure 29). Thus, one of the most interesting properties of wind fields in the Gulf of Finland (that the direction of the strongest winds does not match the direction of the most frequent winds, Soomere and Keevallik, 2003) is not represented in the discussed distributions.

The annual directional distributions of wave approach for Vilsandi and Pakri show a certain interannual and decadal variability but reveal no substantial long-term changes over the entire period of observations. As expected from Figure 29, this distribution has a specific two-peak structure at Vilsandi (Figure 30) and one peak for an almost fixed direction at Pakri.

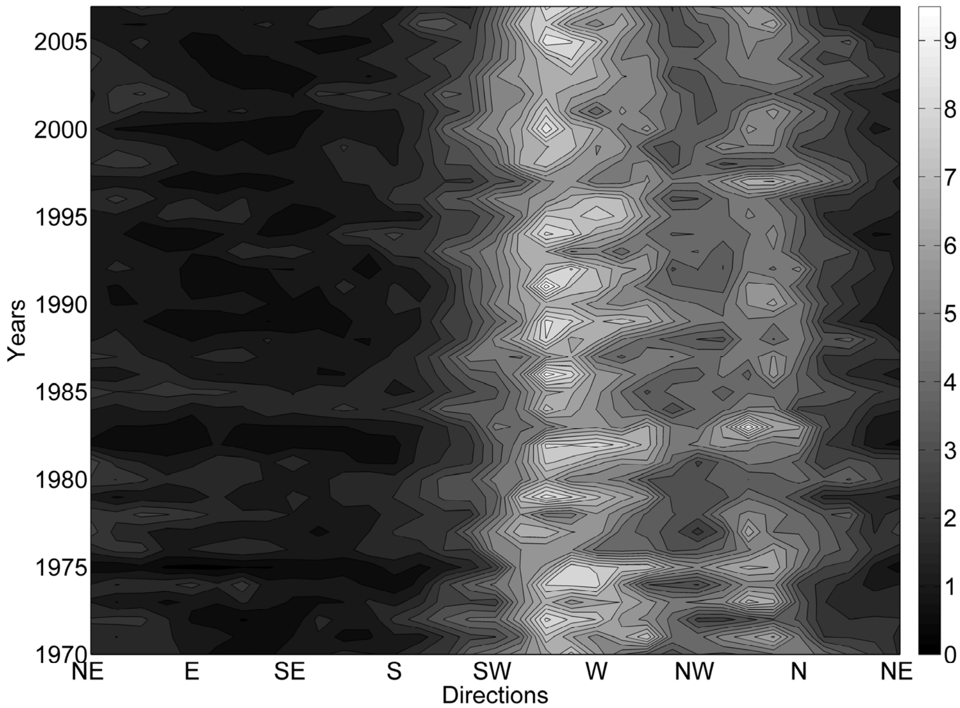

Figure 30. Modelled directional distribution of wave approach for 1970–2007 at Vilsandi. The brightness scale shows the frequency of occurrence (%) of waves from a particular direction

Substantial changes in the predominant wave direction have occurred in Narva Bay during the half-century of observations (Figure 31). Waves mostly approached from the W-NW direction in the 1950s and until about 1965. The predominant propagation direction shifted almost to the north by the 1970s. Further on, it turned considerably, from north-west to 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 mostly been from the south within the last decade. The most frequent propagation direction, therefore, has changed by more than 90º over the last 50 years 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 (Figure 31).

The nature of the described changes obviously needs further research. The observed data about wave propagation do not reflect all wave conditions at Vilsandi where for certain years only wave height has been recorded (Soomere and Zaitseva, 2007). At Narva-Jõesuu and Pakri, the wave direction has been recorded more regularly (Paper III, fig. 7) but still the number of sensible wave direction recordings is smaller than that of 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 the wave heights.

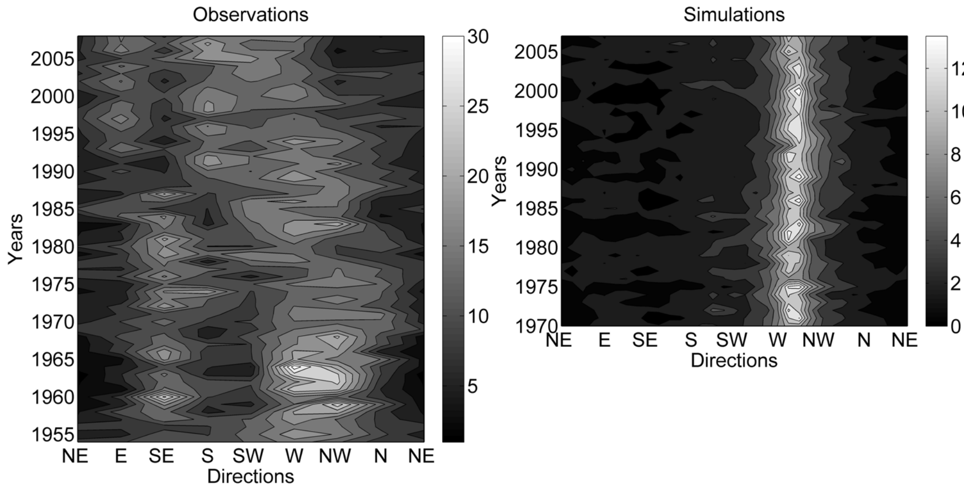

Figure 31. The observed (left panel, 1954–2008) and modelled (right panel, 1970–2007) directional distribution of wave approach at Narva-Jõesuu. The brightness scale shows the frequency of occurrence (%) of waves from a particular direction

Another phenomenon potentially affecting the results in question is that the observer may tend to overestimate the role of relatively short waves, whereas 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 high at Narva-Jõesuu, 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 in fig. 7 of Paper III, concerns only the lengthening of the typical observation season by 1–2 months. As in these months only one observation per day has been possible in daylight, the changing number of observations obviously cannot affect the predominant wave direction very strongly. 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) are behind the described phenomenon.

Conclusions

Summary of the results

The presented results of the model validation for different wind data and against a variety of measured and observed wave data confirm that the particular implementation of the WAM model and the use of the adjusted geostrophic winds are suitable for adequate representation of the typical wave fields in the Baltic Proper and in the deeper nearshore of Estonia for seasons without extensive ice cover. The accuracy of different wind data varies largely in different regions of the Baltic Proper. The MESAN database gives good results in the coastal areas of Sweden, whereas the properly adjusted geostrophic winds are found to be justified for simulation of wave fields in the entire Baltic Proper.

The performed high-resolution long-term numerical simulations of the Baltic Sea waves made it possible to adequately estimate the basic characteristics of the ice-free northern Baltic Sea wave climatology over 38 years (1970–2007). Besides establishing reliable wave statistics, the simulations also qualitatively reproduced time series of wave properties without any systematic bias for selected time intervals in areas open to predominant winds. The results match the long-term average wave height and basic properties of the seasonal pattern of wave intensity in the northern Baltic Proper and in the Gulf of Finland. The match is best for offshore sites and observation places open to the sea, and reasonable for sheltered areas.

The model and forcing used mostly overestimate the occurrence frequency of the most typical wave heights (0.25–0.75 m) for all analysed sites, both offshore and near the coast. The match is best for Pakri where wave observations have been performed in a relatively deep area adjacent to a high cliff.

The analysis of scatter diagrams (joint distributions of wave periods and heights) of the observed and measured wave parameters confirmed that many of the Baltic Sea wave fields, especially during strong storms, are steeper than saturated wave fields with the Pierson–Moskovitz spectrum. Such conditions are frequently connected with acute danger to shipping and other offshore activities.

A direct extension of the analysis of these distributions allows establishing a rough estimate for the combinations of wave heights and periods that most probably will occur in the strongest storms.

The seasonal pattern of wave activity, in general, follows a similar variation in the wind speed, with minor deviations of different nature at different sites, which are probably caused by local ageostrophic features of wind fields or by the frequent presence of ice.

A more detailed analysis of the seasonal course of wind and wave activity revealed an interesting mismatch between the wind and wave properties in different months. Namely, the windiest months are not necessarily the months with the highest average wave activity. In other words, the windiest season does not necessarily coincide with the season with the largest wave activity in the Baltic Sea. The calm and windy seasons for wind and wave conditions occur with a time lag of 0.5–2 months in the NBP. The reasons behind this feature remained unclear within this mostly numerical study and further research is neccessary to shed light on this phenomenon.

The maps of spatial variations in the overall wave intensity, extreme wave heights, wave periods, and their long-term trends form one of the central results of this study. In earlier attempts at reconstructions of the Baltic Sea wave fields similar maps have been constructed for small areas of the basin or have been based on calculations over short time intervals. In this study, for the first time the maps were calculated in relatively high resolution for the entire Baltic Sea by using uniform wind information over the time span (38 years) that is much longer than the time interval (30 years) recommended by the World Meteorological Organization for climatological studies.

The pattern of the average wave intensity over 38 years shows quite large spatial variations. Relatively high average wave heights in the eastern parts of the Bothnian Sea and the north-eastern Baltic Proper match well the overall pattern of predominant south-westerly winds in the northern part of this water body. The presence of areas with relatively high waves south of Gotland and especially in the Arkona basin apparently stems from relatively large wind speeds in the southern Baltic Sea. As a basic change in the wind climate of this area becomes evident as an increase in the strength and frequency of westerly winds (Pryor and Barthelmie, 2003), the southern Baltic Sea may reveal very interesting patterns of change in the overall wave activity. Much of this change is likely to be concentrated in winter (Pryor and Barthelmie, 2003).

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%-iles and 99%-iles) in the north-eastern Baltic Proper and in the western part of the Gulf of Finland. This conclusion does not entirely match the results of several earlier studies. It may reflect 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 fail 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.

Numerical simulations also reveal that no great changes have taken place in the mean and peak wave periods. The changes are quite small, maximally 0.1–0.2 s and thus can be neglected in practical applications. In other words, while quite substantial variations occurred in long-term wave heights, the typical wave periods did not increase considerably in the Baltic Sea over the last 38 years. This feature is not surprising because the wave periods of the Baltic Sea wave fields are largely limited by the fetch length and a relatively small increase in wind speeds leads to quite limited changes in the wave periods.

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 systematic errors and are strongly observer-dependent, the systematic rotation by more than 90º over a half-century can be interpreted as an evidence of certain not yet detected changes in the wind fields over the Gulf of Finland. This turn, however, not necessarily has drastic consequences for the evolution of the sedimentary coasts nearby. The evolution of beaches in Narva Bay is governed by the predominant largest waves that continue to approach from the west to north even when the formal frequency of wave conditions from these directions has somewhat decreased. Waves from southerly directions are small and short and never occur in high water level conditions in Narva Bay. Further understanding of the spatial extent of the described phenomenon and its magnitude in terms of changes in the energy flux are, though, 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 affect the development of coastal areas.

Main conclusions proposed to defend

1. A reliable numerically simulated wind wave climatology has been calculated for the first time in high resolution for ice-free conditions in the entire Baltic Sea over 38 years (1970–2007) with the use of unified, homogeneous wind information and contemporary wave model WAM, and verified against the existing instrumental wave measurements and visual wave observations in the northern Baltic Sea.
2. The use of the properly adjusted geostrophic wind fields is a reasonable way to account for realistic wind fields in the Baltic Sea for long-term wind wave hindcasts. The resulting general statistics and basic trends are reliable but not reconstructions of single extreme storms.
3. The spatial distribution of the overall long-term wave intensity, estimated in terms of average wave heights in the Baltic Sea, is highly anisotropic in the Bothnian Sea and the Baltic Proper. The highest waves (with an average significant wave height up to 1 m) occur in the Arkona basin. The wave intensity is relatively high also in areas south of Gotland, in the eastern parts of the northern Baltic Proper and the Bothnian Sea.
4. The seasonal pattern of long-term wave intensity in Estonian coastal waters follows the seasonal course of wind speed. The season with the highest wave activity (from September to February) is, however, shifted by 0.5–2 months in comparison with the season with the highest wind speeds.
5. The calculated empirical probability density distributions for the occurrence of wave fields with different wave heights and periods have been shown to

adequately match the measured ones for selected sites in the Baltic Proper and along the Estonian coasts.

6. The properties of wave fields in extreme storms in Estonian coastal waters are estimated on the basis of joint distributions of wave conditions with different wave heights and periods. The highest waves once in about 40 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.
7. In many occasions the Baltic Sea wave fields, especially during strong storms, are steeper than saturated wave fields with the Pierson–Moskovitz spectrum. Such conditions may present acute danger to shipping and offshore structures.
8. The long-term changes in the overall wave activity in terms of the annual mean wave height have extensive spatial variability. Wave activity has apparently significantly increased between Bornholm and the German mainland and decreased substantially between Öland and Gotland, and to the south of these islands. Notable increase in wave activity has also occurred near the Latvian coast and Saaremaa.
9. The spatial patterns of extreme wave heights (expressed as thresholds for 95% and 99% of the highest waves a year) qualitatively match similar patterns for the overall wave activity. The largest extreme waves in the northern Baltic Proper occur near the coasts of Saaremaa and Hiiumaa. The relevant long-term trends follow similar trends in the overall wave activity but are less pronounced and show no statistically significant trends in Estonian coastal waters.
10. There has been no significant change in both mean and peak wave periods in the Baltic Sea since 1970. Also, numerically simulated predominant wave directions have been stable. A substantial turn of the predominant observed wave propagation direction by about 90° since about 1980 has been identified from visual observations for Narva Bay. This turn has obviously been caused by ageostrophic wind components.

Recommendations for further work

As discussed above, assessment of wave hindcast fom different wind data against actually measured wave properties has been used by Cox et al. (1998) in order to identify the best quality wind fields from the pool of the NCEP/NCAR reanalyses. Given the existing large biases between the modelled and measured wind data for the Baltic Sea (Ansper and Fortelius, 2003; Keevallik et al., 2010), this methodology has obviously a great potential for improving the quality of atmospheric models in the Baltic Sea basin. This is even more important for adequate modelling of high water levels and patterns of currents.

According to instrumental measurements at Almagrundet (where wave properties were measured with the use of an upward-directed echo sounder (Broman et al., 2006)) and visual observations at Vilsandi (Soomere and Zaitseva, 2007), the annual mean wave height fast increased from the mid-1980s until the middle of the 1990s and rapidly decreased thereafter. At the same time the wind speed measured at Utö continued to increase. This mismatch has led to the question about the reliability and drivers of wave climate changes. This study also touched upon the reliability and causes of these drastic variations in wave intensity, but the reasons behind those still remained unclear. In the light of extensive evidence of substantial intensification of coastal processes on Saaremaa during the last decade (Orviku et al., 2003; Suursaar et al., 2008; Tõnisson et al., 2008), these observations evidently reflect certain changes in wave fields in the 1980s and 1990s. Most probably they stem from specific, ageostrophic features of wind fields in the Baltic Sea basin that are extremely complicated to reproduce with classical meteorological models. This conjecture is implicitly confirmed by the fact that the use of even recently recalculated high-resolution wind fields from the ECMWF did not improve the quality of hindcast of extreme storms in this basin (Section 2.5). As the accuracy of simulations of spatio-temporal patterns in wave properties in extreme storms is invaluable for many applications, further research is necessary in order to clarify this problem.

The above study revealed several differences between numerically estimated and instrumentally measured or visually observed wave statistics. Part of the deviations obviously result from ignoring the ice cover. The ice season usually directly follows the windiest season. This means that the records from offshore waveriders (that are retrieved well before ice formation) contain neither the end of the stormy season nor the relatively calm weather just before the ice is formed. The most reliable data in this respect are those from favourably located coastal sites such as Pakri. In particular, systematic overestimation of the occurrence frequency of wave heights of 0.25–0.75 m by the model may be related to the potential impact of the ice cover on the overall wave statistics. Generally, ignoring the ice should lead to overestimation of modelled wave heights. The presence of ice also causes the recording of a smaller number of low wave conditions and thus an increase in the formal annual average wave height calculated on the basis of available observations (Type A statistics according to Kahma et al., 2003). This is consistent with the fact that the climatological mean wave height in months with frequent ice cover (January–March) is lower than the wave height in October–December. This conjecture, of course, does not mean that a decrease in the length of the ice period would result in smaller overall wave loads to the coast. As the total wave impact covers all the days with waves, it is usually larger in years with less ice cover. A more detailed analysis of the interrelations between actual impact of the (changes to) wave conditions upon the wave activity, therefore, is highly necessary.

The research also highlighted several highly interesting issues that have no direct dynamical or applicational importance, but serve as the background against which some unknown properties of the Baltic Sea wind patterns may be revealed. The most intriguing feature which does have clear importance for wind power studies and estimates of the climate change is the time lag between the windiest season and the season with the highest wave activity in the Baltic Sea. The physical reasons behind this feature are unclear. It may to some extent result from swells approaching from the southern Baltic Sea which are underestimated by the model. It is, however, unlikely that this effect would cause a time lag of about two months at Pakri. Further research is necessary in order to understand this feature and to capture it in models. Although this peculiarity may result from a too low resolution for the definition of the seasons, it still suggests that the wind speed is not the only factor controlling the wave height even in ice-free conditions. This conjecture is supported by the virtual absence of an increase in calculated wave heights in simulations under gradually increasing wind conditions (Suursaar et al., 2008; Paper I).

A straightforward extension of the studies presented above consists in the extension of the wave model towards using (multi-)nested schemes in detailed investigations of wave climate in coastal areas. A specific feature of many Estonian beaches is that they are open to a few directions that not necessarily match the directions of the most frequent or the strongest winds. This peculiarity gives rise to high intermittency of wave fields in wide sections of the Estonian nearshore and in the vicinity of the existing and planned coastal engineering structures. The specific combination of directional distribution of high winds in the Baltic Sea with the complex bathymetry and geometry of the Estonian nearshore suggests that even small changes in the wind patterns (for example, in terms of changes in the direction of the strongest winds, potentially caused by the changes in the trajectories of cyclones) may lead to substantial changes in the severity of wave conditions in semi-sheltered bays. Extensive numerical modelling is the major tool for identification of such changes and for creating measures for mitigation of their consequences.

Finally, the model in use tends to underestimate the maximum wave heights in strong storms, whereas the mismatch considerably varies for different storms. Even the best reconstructions of the marine wind data available to date (inclunding those specifically recalculated for the January 2005 and November 2001 storms by the ECMWF) do not allow reproduction of the course and properties of extreme wavestorms of the past. This feature severely restricts the possibilities of reconstructions of the extremes of the past wave climate and modelling of the roughest wave fields in the future wave climate in the Baltic Sea.

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Papers constituting the thesis

Paper I Räämet, A., Suursaar, Ü., Kullas, T. and Soomere, T., 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *Journal of Coastal Research,* Special Issue 56, Part I, 257–261.

Paper II 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.

Paper III 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.

Paper IV Soomere, T., Zaitseva-Pärnaste, I. and Räämet, A., 2010. Seasonal and long-term variations in wave conditions in Estonian coastal waters. *Boreal Environment Research* (submitted).

Abstract

This study makes an attempt to merge numerically simulated, instrumentally measured and visually observed wave properties in the northern Baltic Proper and on the Estonian coast to reveal the basic features of wave fields and their trends. The wave climatology is calculated numerically in high resolution (3 miles) for the entire Baltic Sea over 38 years (1970–2007) by the WAM wave model driven by adjusted geostrophic winds under ice-free conditions. The results are verified against the existing instrumental wave measurements in the northern Baltic Proper and visual wave observations along the Estonian coast. The model adequately replicates the seasonal patterns of wave intensity and the probability distribution functions for different wave heights in both offshore and coastal regions of the northern Baltic Proper and the Gulf of Finland. The resulting wave statistics (incl. empirical probability density distributions for the occurrence of wave fields with different wave heights and periods) and basic trends are reliable but reconstructions of single extreme storms are not always exact. The best match between the modelled and measured data is at Vilsandi and Pakri.

Wave conditions in different parts of the Baltic Sea vary considerably owing to the complex geometry and anisotropy of dominating winds of this water body. The spatial distribution of the overall long-term wave intensity is highly anisotropic in the Bothnian Sea and the Baltic Proper. The areas of the largest overall wave activity are located in the eastern parts of the Bothnian Sea and northern Baltic Proper, south of Gotland, and in the Arkona basin.

The seasonal pattern of long-term wave intensity in Estonian coastal waters follows the seasonal course of wind speed. The windiest season (September–February) and the time with the largest measured or modelled wave activity (October–March) occur with a time lag of 0.5–2 months.

The long-term changes in the overall wave activity have extensive spatial variability and show a significant increase between Bornholm and the German mainland, a notable increase near the Latvian coast and Saaremaa and a substantial decrease between Öland and Gotland, and to the south of these islands. In general, the wave intensity has decreased in the western part and increased in the eastern part of the Baltic Sea. There were almost no changes in wave activity in the northern part of the Baltic Proper.

The properties of wave fields in extreme storms in Estonian coastal waters are estimated on the basis of joint distributions of both modelled and observed wave conditions with different wave heights and periods. In many occasions the Baltic Sea wave fields, especially during strong storms, are steeper than saturated wave fields with the Pierson–Moskovitz spectrum. The spatial patterns of extreme wave heights (thresholds for 95% and 99% of the highest waves) and their long-term trends qualitatively match similar patterns for the overall wave activity but show no statistically significant trends in Estonian coastal waters. Both mean and peak wave periods and simulated predominant wave directions have been mostly stable since 1970. Significant changes in the directional distribution of waves observed at Narva-Jõesuu since the 1980s are not represented in hindcasts.

Resümee

Käesolevas töös määratakse laineväljade põhiomadused ja nende trendid Läänemere põhjaosas ning Eesti rannavetes numbriliselt modelleeritud, instrumentaalselt mõõdetud ning visuaalselt vaadeldud lainetuse parameetrite alusel. Lainete klimatoloogia on modelleeritud 3-miilise (ligikaudu 5,5 km) lahutusvõimega lainemudeliga WAM Rootsi Meteoroloogia ja Hüdroloogia Instituudi geostroofilise tuule alusel 38-aastase perioodi jaoks (1970–2007) jäävabades tingimustes. Modelleeritud tulemuste võrdlus olemasolevate instrumentaalsete lainetuse mõõtmistega Läänemere põhjaosas ning visuaalsete vaatlustega Eesti rannikul näitab, et mudel taastab kvalitatiivselt lainekõrguste aegjada ja reprodutseerib hästi lainetuse intensiivsuse sesoonse muutlikkuse ning erinevate lainekõrguste esinemise tõenäosuse mere avaosas ja Soome lahes nii ranniku lähistel kui ka avamerel. Saadud lainetuse statistika ning põhilised trendid on usaldusväärsed, kuid üksikute tormide taastamine ei ole alati korrektne. Kõige paremini kattuvad modelleeritud väärtused vaatlusandmetega Vilsandil ja Pakril.

Lainetuse tingimused Läänemere erinevates osades varieeruvad märgatavalt mere keeruka geomeetria ja valitsevate tuulte anisotroopia tõttu. Aasta keskmise lainekõrguse ruumiline jaotus on tugevalt anisotroopne. Suurima lainetuse intensiivsusega alad paiknevad Botnia mere ja Läänemere põhjaosa idapoolses sektoris, Gotlandi saarest lõunas ning Arkona basseinis.

Lainekõrguse sesoonne muutlikkus Eesti rannikuvetes järgib tuulekiiruse sesoonset muutlikkust. Tuulise aastaaja (septembrist veebruarini) ja suurima lainetuse aktiivsusega perioodi (modelleeritud andmetes oktoobrist märtsini) vahel on ajaline nihe 0,5 kuni 2 kuud.

Pikaajalised muutused lainekõrguses on mere erinevates osades oluliselt erinevad. Vaadeldaval ajavahemikul on lainekõrgus oluliselt kasvanud Bornholmi ja Saksamaa mandriosa vahel, märgatavalt suurenenud Läti ranniku ja Saaremaa lähistel ning märkimisväärselt langenud Ölandi ja Gotlandi vahel ning nendest saartest lõunas. Üldjoontes on lainetuse intensiivsus kahanenud Läänemere lääneosas ja kasvanud idaosas; mere põhjaosas on muutused olnud marginaalsed.

Lainetuse omadused ekstreemsetes tormides Eesti rannikuvetes on määratud lainete kõrguste ja perioodide kombinatsioonide statistika baasil, mis on leitud nii numbriliselt kui vaatlusandmetest. Paljudel juhtudel, eriti just tugevate tormide ajal, on Läänemere laineväljad järsemad kui Pierson–Moskovitz'i spektriga küllastunud laineväljad. Ekstreemsete lainekõrguste (5% ja 1% tõenäosusega esinevad lained ehk lainetuse 95% ja 99% protsentiilide) ruumilised mustrid ning nende pikaajalised trendid kattuvad kvalitatiivselt lainekõrguse analoogiliste mustritega, kuid vastavad trendid Eesti rannikuvetes pole statistiliselt olulised. Lainete modelleeritud keskmised ja tipp-perioodid ning modelleeritud valdavad lainelevi suunad on olnud stabiilsed alates 1970ndast aastast. Olulised muutused vaadeldud lainelevi suundades Narva-Jõesuus alates 1980ndast aastast ei kajastu modelleeritud tulemustes.

Appendix A: Curriculum Vitae

1. Personal data

Name	Andrus Räämet
Date and place of birth	10.05.1979, Tallinn

2. Contact information

Address	Ehitajate tee 5, 19086, Tallinn
Phone	(+372) 620 25 61
e-mail	andrus.raamet@ttu.ee

3. Education

Educational institution	Graduation year	Education (field of study/ degree)
Tallinn University of Technology	2003	Civil engineering / Master of Science in Engineering
Tallinn University of Technology	2001	Civil engineering / Bachelor of Science in Engineering

4. Language competence/skills (fluent, average, basic skills)

Language	Level
Estonian	native language
English	average
Finnish	average

5. Further training

Period	Educational or other organisation
August 2007 – September 2007	International Summer School "Waves and coastal Processes", Tallinn University of Technology
Spring term 2007	Helsinki University of Technology, Laboratory of Structural Mechanics

6. Professional employment

Period	Organisation	Position
Oct. 2009 – to date	Tallinn University of Technology, Institute of Cybernetics	Researcher

Sept. 2006 – to date	Tallinn University of Technology, Department of Mechanics	Assistant
Sept. 2005 – June 2006	Tallinn University of Technology, Department of Mechanics	Contract job
Sept. 2003 – Aug. 2006	Tallinn University of Technology, Facilities Management Services	Project leader
Sept. 2001 – June 2003	Tallinn University of Technology, Department of Mechanics	Contract job
April 2001 – Sept. 2002	Civen OÜ	Technician

7. Scientific work

7.1. Publications

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

Räämet, A., Suursaar, Ü., Kullas, T. and Soomere, T., 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *Journal of Coastal Research,* Special Issue 56, Part I, 257–261.

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.

Soomere, T., Zaitseva-Pärnaste, I. and Räämet, A., 2010. Seasonal and long-term variations of wave conditions in Estonian coastal waters. *Boreal Environment Research* (submitted).

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. and Zaitseva-Pärnaste, I., 2008. Far-field vessel wakes in Tallinn Bay. *Estonian Journal of Engineering*, 14 (4), 273–302.

Articles published in conference proceedings (3.4):

Räämet, A. and Soomere, T., 2010. A reliability study of wave climate modelling in the Baltic Sea. In: *6th Study Conference on BALTEX*, 14–18 June 2010, Miedzyzdroje, Island of Wolin, Poland (accepted).

Conference abstracts (5.2):

Räämet, A., 2008. On the variability of the Baltic Sea wave fields. In: *3rd International student conference "Biodiversity and functioning of Aquatic Ecosystems in the Baltic Sea Region", 9–12 October 2008, Klaipeda, Lithuania, Abstracts*, p. 42.

Räämet, A., Suursaar, Ü., Kullas, T. and Soomere, T., 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. In: *The 10th International Coastal Symposium, 13–18 April 2009, Lisbon, Portugal, Book of Abstracts*, p. 59.

Räämet, A., 2009. Simulating long-term changes of wave conditions in the northern Baltic Sea. In: *7th Baltic Sea Science Congress, 17–21 August 2009, Tallinn, Estonia, Abstract Book*, p. 149.

Räämet, A. and Soomere, T., 2009. Wave climate changes in the Baltic Proper 1978–2007. In: *4th International student conference "Biodiversity and functioning of Aquatic Ecosystems in the Baltic Sea Region", 2–4 October 2009, Dubingiai, Lithuania, Abstracts*, p. 17.

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

7.2. Conference presentations

Räämet, A., 2008. On the variability of the Baltic Sea wave fields. Poster presentation at the 3rd International student conference *"Biodiversity and functioning of Aquatic Ecosystems in the Baltic Sea Region"*, 9–12 October 2008, Klaipeda, Lithuania.

Räämet, A., Suursaar, Ü., Kullas, T. and Soomere, T., 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. Oral presentation at the 10th International Coastal Symposium, 13–18 April 2009, Lisbon, Portugal.

Räämet, A., 2009. Simulating long-term changes of wave conditions in the northern Baltic Sea. Oral presentation at the 7th Baltic Sea Science Congress, 17–21 August 2009, Tallinn, Estonia.

Räämet, A. and Soomere, T., 2009. Wave climate changes in the Baltic Proper 1978–2007. Oral presentation at the 4th International student conference *"Biodiversity and functioning of Aquatic Ecosystems in the Baltic Sea Region",* 2–4 October 2009, Dubingiai, Lithuania.

Räämet, A. and Soomere, T., 2010. A reliability study of wave climate modelling in the Baltic Sea. Oral presentation at the *6th Study Conference on BALTEX*, 14–18 June 2010, Międzyzdroje, Island of Wolin, Poland.

Zaitseva-Pärnaste, I., Räämet, A. and 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 (accepted).

8. Defended theses

Master's degree thesis "Analytical and experimental study of timber structures nail plate joints"

9. Main areas of scientific work/Current research topics

Spatio-temporal variability of the Baltic Sea wave fields in changing climatic conditions.

Appendix B: Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Andrus Räämet
Sünniaeg ja -koht	10.05.1979, Tallinn

2. Kontaktandmed

Aadress	Ehitajate tee 5, 19086, Tallinn
Telefon	(+372) 620 25 61
e-mail	andrus.raamet@ttu.ee

3. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2003	Ehitustehnika / Tehnikateaduste magister
Tallinna Tehnikaülikool	2001	Ehitustehnika / Tehnikateaduste bakalaureus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti	emakeel
Inglise	kesktase
Soome	kesktase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
August 2007 – September 2007	Rahvusvaheline suvekool "Lained ja rannikuprotsessid", Tallinna Tehnikaülikool
Kevadsemester 2007	Helsingi Tehnikaülikool, Ehitusmehaanika labor

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
Okt. 2009 – tänaseni	Tallinna Tehnikaülikool, Küberneetika instituut	Teadur
Sept. 2006 – tänaseni	Tallinna Tehnikaülikool, Mehaanikainstituut	Assistent

Sept. 2005 – Juuni 2006	Tallinna Tehnikaülikool, Mehaanikainstituut	Lepinguline töötaja
Sept. 2003 – Aug. 2006	Tallinna Tehnikaülikool, Haldusosakond	Projektijuht
Sept. 2001 – Juuni 2003	Tallinna Tehnikaülikool, Mehaanikainstituut	Lepinguline töötaja
Aprill 2001 – Sept. 2002	Projekteerimisbüroo Civen OÜ	Tehnik

7. Teadustegevus

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

8. Kaitstud lõputööd

Magistritöö "Puitkonstruktsioonide naelplaatliidete analüütiline ja eksperimentaalne uurimine"

9. Teadustöö põhisuunad

Läänemere lainetuse tingimuste ajalis-ruumiline muutlikkus muutuvates kliimatingimustes.

Paper I

Räämet, A., Suursaar, Ü., Kullas, T. and Soomere, T., 2009. Reconsidering Uncertainties of Wave Conditions in the Coastal Areas of the Northern Baltic Sea. *Journal of Coastal Research,* Special Issue 56, Part I, 257–261.

Paper II

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.

Paper III

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.

Paper IV

Soomere, T., Zaitseva-Pärnaste, I. and **Räämet, A.**, 2010. Seasonal and long-term variations in wave conditions in Estonian coastal waters. *Boreal Environment Research* (submitted).