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Changing properties of wind waves and vessel wakes on the eastern coast of the Baltic Sea

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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.

/Loreta Kelpšaitė/ 

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Tuulelainete režiimi ja laevalainete omaduste muutused Läänemere idarannikul

LORETA KELPŠAITĖ

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THE BREAKING OF A WAVE
CANNOT EXPLAIN THE WHOLE SEA...

Vladimir Nabokov,
"The Real Life of Sebastian Knight"

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KEYWORDS: wave energy flux, coastal zone, wave climate, Baltic Sea, marine natural hazards, ship wakes, energy pollution.

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Introduction

Coasts under pressure

The marine coasts have a specific role not only as the interaction region between water masses and dry land, but also as a zone of extremely intense energy and momentum conversion. It is well known that different coasts are vulnerable to different hazards. For example, tsunami and storm surges affect strongly the coasts that have extensive relatively shallow shelf areas. On the other hand, increase in sea level is virtually insignificant for the functioning of many estuaries of large rivers, because the sedimentation rate at their mouths several times exceeds the effect of sea level rise.

The coasts of the Baltic Sea are under gradually growing pressure of different marine hazards. Changes in the water level during last decades have been well identified around the entire Baltic Sea (Kont et al., 2003; Dailidienė et al., 2004, 2006; Johansson et al., 2004; IPCC, 2007; BACC, 2008, among others). Much less attention has, however, been paid to potential changes in the properties of wind waves. Several cases of hazardous wave conditions that occurred at the turn of the millennium (Kahma et al., 2003) and ferocious winter storms of 2004/2005 (Suursaar et al., 2006; Soomere et al., 2008a) have reinforced the discussion as to whether the extreme wave conditions in the Baltic Sea are rougher than situation a few decades ago. In particular, windstorm Gudrun (Erwin), the fourth most expensive natural disaster in the world in 2005 that hit many areas in northern Europe on 7–9 January 2005, caused extensive property damage and exceptionally high coastal flooding on its way. The storm surge in the Estonian city of Pärnu was the highest ever recorded (275 cm over mean sea level, Suursaar et al., 2006). The most extreme were, however, wave conditions during this storm when the significant wave height near the Island of Saaremaa evidently reached 9.5 m (Soomere et al., 2008a), whereas the maximum measured wave height in this basin is 7.8 m (Broman et al., 2006).

Studies concerning properties of complex wave fields in different sea areas and the understanding of both the status of and changes in the wave regime (more generally, wave climate) undoubtedly form one of the key elements of contemporary physical oceanography and coastal science. This is not only because surface waves are a major driver of processes in the surface layer, nearshore and coastal area, including many phenomena related to coastal floodings such as the wave set-up (Dean and Dalrymple, 1991), but also because the wave climate is one of the most sensitive indicators of changes in the wind regime and local climate in semi-enclosed sea areas. The large damaging potential of high storm waves, particularly in conditions of high water levels, motivates treating surface waves and wave-induced impacts on the coasts as an intrinsic component of marine-induced hazards to the coastal zone.

The complexity of physics and dynamics of the Baltic Sea extend far beyond the typical features of many other water bodies of comparable size (Wulff et al., 2001; BACC, 2008). This basin is characterized by extremely complex geometry, highly varying wind fields, extremely rough wave conditions at times, extensive archipelago areas with specific wave propagation properties and ice cover during a large part of each year. The combination of a relatively small size and the vulnerability of its ecosystem makes this region particularly susceptible to climate changes and shifts.

Numerous changes in the forcing conditions and in the reaction of the water masses of the Baltic Sea have been reported during the latter decades (BACC, 2008; Soomere et al., 2008a). There is evidence that the increasing storminess in the Baltic Sea region starting from the 1970s (Alexandersson et al., 1998) has already caused extensive erosion of the depositional coasts (Orviku et al., 2003). This trend, however, has been severely questioned by many authors. For example, the changes in the wave climate of some parts of the region have been found to be marginal, at least, until the mid-1990s (WASA, 1995; Mietus and von Storch, 1997). Moreover, the intensity and duration of severe wave height events in the southern North Sea have decreased since about 1990–95 (Weisse and Günther, 2007). This decrease is consistent with the updated trends of storminess (Alexandersson et al., 2000).

Changing properties of wave fields

Recognition of wave climate changes, in particular changes in extremes, requires a thorough knowledge of the typical and extreme wave conditions. The global wave data set KNMI/ERA-40 Wave Atlas (1957–2002, Sterl and Caires, 2005) allows the production of reliable wave climatology for open ocean conditions based on 6-hourly means of wave properties over an average of 1.5°×1.5° areas. This resolution is too coarse for the Baltic Sea conditions.

The historical wave data sets from the coastal areas of the northern Baltic Sea recently re-analysed or digitised have revealed highly interesting features of long-term variability in wave conditions. Apparently wave activity increased gradually from the 1980s until the mid-1990s, and was followed by a drastic decrease in the annual mean wave height until about the year 2005 (Broman et al., 2006; Soomere and Zaitseva, 2007). This feature is obviously connected neither with changes in the wind speed nor with changes in the wind direction (Soomere and Zaitseva, 2007). Moreover, it does not become evident in the southern Baltic Sea (Cieślikiewicz and Paplińska-Swerpel, 2008), and is not reproduced by simple one-point wave models (Suursaar and Kullas, 2009).

These inconsistencies motivate further analysis of available historical wave data in order to obtain a more adequate picture of regional differences in wave climate variability. Relevant studies may also shed some light into the patterns of long-term changes in wind climate over the Baltic Sea. An important advantage of visual wave observations (that started in the middle of the last century almost simultaneously on the entire eastern part of the Baltic Proper) is that they were performed according to a unified methodology and thus are easily comparable.

Owing to the extremely complex geometry and bathymetry of the Baltic Sea, it is frequently 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. This method has been extensively used for many areas of the Baltic Sea in the recent past (e.g. Paplinska, 1999, 2001; Cieslikiewicz and Herman, 2002; Soomere, 2003, 2005a, 2008). Most of the reconstructions are, however, either limited to relatively short periods of a few years, or are concentrated 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; Räämet et al., 2009).

The most important source of the uncertainties in the hindcasts of wave fields is the low quality of the relevant wind fields. 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 contemporary wave models are used (Räämet et al., 2009).

Much more adequate results have been obtained for semi-sheltered sea areas with a short memory of wave fields (Soomere, 2005a). There is increasing interest in the properties of wind waves in several such areas connected with the damaging potential of wakes from large, fast vessels. The contribution of ship traffic to local hydrodynamic activity in confined waters has been known for a long time. Heavy ship traffic has the obvious potential for causing environmental damage in the vicinity of vulnerable areas such as wetlands or low-energy coasts. Vessel wakes can cause extensive shoreline erosion, resuspend bottom sediments, trigger ecological disturbance or harm the aquatic wildlife (Schoellhamer, 1996; Bourne, 2000; Parnell and Kofoed-Hansen, 2001).

Owing to the increase in the number, speed, and size of ships over the last few decades, vessel wakes may be a significant driver of hydrodynamics on some coasts that are exposed to relatively high natural hydrodynamic loads. Such a situation was first identified a few years ago for several sections of Tallinn Bay (Soomere and Rannat, 2003; Soomere, 2005b).

The continuing high level of ship wave activity in Tallinn Bay (Parnell et al., 2008) and in similar sea areas produces concerns about the potential impact of ship wakes on vulnerable coasts. In the light of the United Nations Convention on the Law of the Sea (UNCLOS[1]), the excess hydrodynamic activity in coastal areas affected by high vessel wakes should be interpreted as a specific type of pollution.

[1] http://www.un.org/Depts/los/convention_agreements/texts/unclos/unclos_e.pdf

This would be a natural extension of the definition of pollution that today is commonly understood as releasing certain substances or noise into the environment (Stumbo et al., 1999; IMO, 2000). An adequate estimate of the tolerable level for ship wave activity can only be based on comprehensive knowledge about properties of both ship-induced and wind-generated waves.

Layout of the thesis

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 indexed by the ISI Web of Science:

Paper I Valdmann, A., Käärd, A., **Kelpšaitė, L.,** Kurennoy, D., Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica*, **21**(1-2), 3–12.

Paper II **Kelpšaitė, L.,** Herrmann, H., Soomere, T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proceedings of the Estonian Academy of Sciences*, **57**(4), 225–231.

Paper III **Kelpšaitė, L.,** Parnell, K. E., Soomere, T. 2009. Energy pollution: the relative influence of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea. *Journal of Coastal Research*, Special Issue 56, 812–816.

Peer-reviewed paper in the international research journal:

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

The role of the applicant in these papers is as follows.

The applicant had the leading role in the collection of historical data from wind wave observation sites in Lithuania and their analysis, examination of ship wake properties for the comparison with analogous properties of natural waves in the study area, performing an analysis of wave fields precomputed with the use of the WAM model and writing Papers II and III.

In case of Paper I, the candidate was responsible for the estimation of the potential role of the generic marine hazards upon the Lithuanian coast, collection of the relevant historical data and writing the relevant parts of the paper. The basic contribution of the applicant to Paper IV consists in the participation in the field experiment, parallel analysis of the gathered ship wave data and in writing the relevant parts of the text.

The thesis starts with the identification of the potential impact factors of large-scale marine coastal hazards along the eastern coast of the Baltic Sea (Chapter 1). The presentation largely follows Paper I. A certain part of it has been assembled based on the results of existing publications on this topic, which have been combined with the local, specific properties of the Baltic Sea coasts and their forcing factors. This is followed by an overview of the experience in mitigation of the most devastating marine coastal hazards for similar coasts in other parts of the world. This experience is discussed in detail in two selected coastal sections – the coasts of Lithuania and the coasts of Tallinn Bay. These sections are representative of a large part of the eastern coast of the Baltic Sea, namely, of relatively straight, mostly wave-dominated sandy coasts in eastern Germany, Poland, Latvia and southern Estonia, and of highly variable, partially urbanised and low-lying bayhead coasts along the southern coast of the Gulf of Finland.

On the one hand, the presentation aims at a comprehensive description of hydrodynamically driven hazards along a large part of the Baltic Sea coasts for sustainable management of these coasts. On the other hand, the discussion attempts to identify and, whenever possible, to indicate ways of filling the gaps in the existing knowledge in the scientific background in these selected areas and depict the needs for the further research necessary for sustainable management and building effective countermeasures to marine coastal hazards.

Other chapters of the thesis focus on one of the major driving forces of the local coastal processes – wave conditions in the eastern part of the Baltic Sea and their changes. Chapter 2 presents an overview of the wind wave climate at the eastern coast of the Baltic Sea over the years 1993–2005. The ability of the visually observed wave data to represent general features of the open sea wave fields and the basic properties of the wave climate is discussed for the Lithuanian coast. As the same observation methodology has been used in all historical visual wave observations on the eastern coast of the Baltic Sea, it is straightforward to compare the relevant data sets from different parts of the Baltic Proper. The results of the analysis of typical wave properties and interannual and decadal variations in the annual mean wave height are presented in Paper II.

Chapter 3 is based on Papers III and IV and focuses on the estimation of the role of wakes from high-speed ferries in the budget of wave energy and its flux for semi-sheltered beaches in fetch-limited environments. A semi-sheltered mixed sand-gravel beach on the south-western coast of the Island of Aegna at the entrance to Tallinn Bay in the central part of the Gulf of Finland, the Baltic Sea, is chosen as an example of such beaches. The properties of ship wakes and energy and energy flux carried by these waves are estimated based on the data collected during an experiment in summer 2008 (Paper IV). The properties of wind waves for 1981–2008 are estimated with the use of a multi-nested version of the wave model WAM forced with high-quality one-point wind data from the neighbourhood of the study site (Paper III). One of the main outcomes of the relevant research is that the changes in the wave climate owing to intense fast ferry traffic can evoke changes in the functioning of the coastal environment.

Approbation of the results

The main results described in this thesis have been presented in the following international conferences, symposiums and workshops:

Conferences:

US/EU-Baltic 2008 International Symposium "Ocean Observations, Ecosystem - Based Management & Forecasting", 27–29 May 2008, Tallinn, Estonia (2008); oral presentation: L. Kelpšaitė "Wave climate variability in the Tallinn area" (27 May 2008).

The International Conference (school-seminar) on the Dynamics of Coastal Zone of Non-tidal Seas, 1–4 July 2008, Baltiysk, Russia; poster presentation: L. Kelpšaitė, "Value of the depth of closure at the different Lithuanian sea coast points" (1 July 2008).

Third Regional Student Conference "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", 9–13 October 2008, Juodkrantė, Lithuania; oral presentation: L. Kelpšaitė "Wave regime variations at the Lithuanian coast of the Baltic Sea" (10 October 2008).

Marie Curie network SEAMOCS network meeting and conference on fatigue, 23–24 October 2008, Oslo, Norway; oral presentation: L Kelpšaitė, I. Zaitseva-Pärnaste "Wave regime changes at the Baltic Sea Eastern coast" (23 October 2008).

Interdisciplinary workshop "Effects of climate change: coastal systems, policy implications, and the role of statistics" of Marie Curie networks SEAMOCS, 18–20 March 2009, Malta; poster presentation: L. Kelpšaite, T. Soomere "Energy pollution: The relative influence of wind-waves and vessel-wake energy in Tallinn Bay, Baltic Sea".

Second regional conference "Sea and coastal research 2009", 8–10 April 2009, Nida, Lithuania; oral presentation: L. Kelpšaite, T. Soomere "Estimation of wave induced sediment transport at Aegna Island, Tallinn Bay" (10 April 2009).

10th International Coastal Symposium 13–18 April 2009, Lisbon, Portugal; oral presentation: L. Kelpšaite, K. E. Parnell, T. Soomere "Energy pollution: the relative influence of wind-wave and vessel-wake energy: Tallinn Bay, the Baltic Sea" (14 April 2009).

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1 Marine hazards to the northern and eastern parts of the Baltic Sea

1.1 Introduction

The Baltic Sea is a highly interesting water body. Owing to its size, sheltered nature and high variability of coasts, the major potential marine hazards affecting its different coasts are very diverse. In this chapter, an overview of scientific information is presented about hazards that are the most acute for the northern and eastern parts of the Baltic Sea.

While several classical hazards such as tsunamis are immaterial here, changes in sea level and its variability, wave regime and wind-induced coastal flooding can significantly impact coastal environments. Recent advances in detecting, analysis and quantification of the influence of the natural hazardous factors and their changes in different Baltic Sea regions are described in Paper I together with a discussion of promising technologies for the monitoring of changes to the coasts and ways of mitigation of marine hazards.

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. They bring to the coastline massive amounts of energy and thus form one of the generic sources of hazards in the coastal zone. Another basic hazard is the local, wave-induced change in sea level and sea level change induced wave climate modifications. These and similar hazards that may considerably affect the coasts are called wave-induced marine hazards below. Also the importance of the changing wave energy climate for the marine system is discussed.

Section 1.2 presents a general description of the basic features of the Baltic Sea coasts that are relevant from the viewpoint of the analysis and mitigation of marine hazards. Section 1.3 focuses on the methods for the identification of the potential large-scale marine coastal hazards along the eastern coast of the Baltic Sea. This part is followed by an overview of the experience in mitigation of the most devastating marine coastal hazards for similar coasts in other parts of the world.

1.2 The Baltic Sea and its coasts

The Baltic Sea (Fig. 1.1) is a unique water body in many aspects, with quite a large size, specific hydrographical characteristics, complexity of circulation and limited connections with the World Ocean. It is frequently said that it combines features of a large lake, large estuary and small ocean (BACC, 2008; Leppäranta and Myrberg, 2008). The intricacy of its internal dynamics extends far beyond the typical features of basins of comparable size (Alenius et al., 1998; Soomere et al., 2008b). The susceptibility of this water body to adverse impact has been internationally recognised by the International Maritime Organization declaring the Baltic Sea as a particularly vulnerable sea area at the end of 2005. The combination of the relatively small size of the Baltic Sea and the vulnerability of its ecosystem and its comparatively young coasts makes this region extremely susceptible to both climate changes and anthropogenic pressure.

Classical earthquake- or landslide-generated tsunamis present no acute danger in the Baltic Sea region. A large tsunami may only occur in a highly improbable case where a large asteroid directly hits the Baltic Sea.

A more subtle issue is the problem of salinisation of the groundwater and soil in the coastal zone. There is an overall excess of precipitation in the Baltic Sea countries. The groundwater flux is generally from mainland to sea and the threat of salinisation is fairly minor. For the listed reasons these phenomena are not analysed below.

The description of wave-based coastal hazards along the western and northern parts of the Baltic Sea is also intentionally left aside. These coastal areas are mostly of skären type, composed of extremely stable bedrock formations, and are generally uplifting. Thus, they have largely different hazardous factors.

A number of changes in the forcing conditions and the reaction of the water masses of the Baltic Sea observed during the 1990s and 2000s (BACC, 2008; Soomere et al., 2009) can be related to a more frequent occurrence of marine hazards affecting the evolution of its coasts (Orviku et al., 2003). This opinion is supported by the analysis of Johansson et al. (2001), who showed that the probability of high water levels has increased considerably within the last half-century. Although the changes in the wave climate have been found marginal, at least, until the mid-1990s (WASA, 1998) and an even decreasing tendency of annual average wave heights since about 1997 has recently been identified (Broman et al., 2006; Soomere and Zaitseva, 2007), a combination of unusually high water levels and rough seas presents acute danger to depositional coasts.

The anisotropic nature of the Baltic Sea wind and wave fields (Jönsson et al., 2002, 2005; Soomere, 2003; Räämet et al., 2009) suggests that the eastern coast is probably under the largest natural pressure (in terms of wave-induced hydrodynamic loads and storm surges) among the variety of the coasts of this water body. This coast is to a large extent in active evolution and potential changes in the forcing are expected to become evident relatively fast. It hosts several major ports and cities which may be substantially affected by different marine coastal hazards. The potential increase in the frequency and/or severity of such hazards may have great impact on the planning, operation, maintenance and reconstructions of the relevant infrastructure.

The eastern coast of the Baltic Sea includes different coast types. The coast of Lithuania represents a generic type of more or less straight, high-energy (in the Baltic Sea conditions), actively developing coasts that contain a relatively large amount of finer, mobile sediments, are open to predominating wind directions in this water body and are exposed to wave activity for a wide range of wave approach directions. As mentioned above, such coasts frequently occur along a large part of the southern and eastern coasts of the Baltic Sea from Germany to southern Estonia. For this reason, one of the focuses of Paper I processes and threats in the Lithuanian coastal sector.

Fig. 1.1. Location scheme of the Baltic Sea

The coasts of Estonia north of Pärnu, however, show a large variability, the comprehensive analysis of which is out of the scope of this study. The analysis below and in Paper I concentrates on the processes and hazards typical of densely populated (albeit not necessarily urban or artificial) coasts. Typical examples of such coasts form the coastal sections of the city of Tallinn, where a number of different threats may become evident.

These coasts are characteristic of the eastern and southern parts of the Gulf of Finland. They were formed and develop predominantly under the effect of wave action (Orviku and Granö, 1992). A recent overview of the available scientific literature addressing coastal processes in this area is presented by Soomere et al. (2007). The Estonian coast of this gulf hosts numerous peninsulas, islands, and bays cutting deep into the land. The beaches form a large erosional-accretional system, divided into compartments by rocky peninsulas and headlands. The volume of finer sediments and the magnitude of littoral drift are modest. The most common types of coasts here are the straightening, accumulation and embayed coasts (type 20 according to Kaplin, 1973).

The distinguishing feature of such coasts is the high spatio-temporal variability of the vulnerability with respect to wind- and wave-induced coastal hazards. These coasts are usually sheltered for most of the wind directions. Coastal hazards become evident relatively seldom here whereas the sections where they occur depend largely on the local features of each hazardous (e.g. storm) event.

In addition to the analysis of the forcing factors, Paper I also addresses the experience of mitigation of the most devastating marine coastal hazards for similar coasts, discusses the gaps in the existing knowledge in these two areas and depicts the needs for further research necessary for building effective countermeasures.

1.3 Wave field and its changes

Wave action is the principal driving force of the coastal processes (Dean and Dalrymple, 2002). The most intensive wave activity can be observed on open ocean coasts where wave heights over 10 m may occur regularly. As many beaches are vulnerable to the joint occurrence of a high water level and large waves, even short-lived but ferocious storms can cause rapid erosion and accretion. The most extensive damage in vulnerable areas (such as low-lying atolls and the coastal fringes of high islands) usually occurs during short wave events created by strong cyclones. Even infrastructure perched on 20 m high cliffs may not be immune during severe storms (Solomon and Forbes, 1999). On the other hand, the role of even small waves may be very large under unfortunate conditions (see Dean and Dalrymple, 2002 for examples).

The relative importance of wave activity is particularly large in micro-tidal and non-tidal water bodies. The tidal range in the Baltic Sea is well below 10 cm and is typically 2–4 cm along its eastern coast (Leppäranta and Myrberg, 2008). Wave activity is therefore the foremost driver of the coastal processes along the south-eastern coast of the Baltic Sea and in many sections of its sub-basins. The actual patterns of coastal changes are frequently modified by transient decadal and sub-decadal water level changes.

Owing to specific features of the Baltic Sea wind fields (Mietus, 1998; Soomere and Keevallik, 2001, 2003), even relatively sheltered bays are at times subject to extensive wave loads (Soomere, 2005a). For example, the almost entire coastal area of the City of Tallinn is completely sheltered from waves excited by predominating south-western winds. As a result, its local wave climate is mild compared to that in the open part of the Gulf of Finland. The annual mean significant wave height varies from 0.29 m to 0.32 m in different sections of Pirita Beach in the city of Tallinn (Soomere et al., 2007). Western winds, however, may bring to this area wave energy stemming from the northern sector of the Baltic Proper. Northern and north-western winds may excite waves in this bay that are almost as high as the highest waves in the Gulf of Finland. The significant wave height exceeds 2 m each year and may reach 4 m in NNW storms in the central part of Tallinn Bay (Soomere, 2005a). This feature well explains why most of the coasts of Tallinn Bay show features of intense erosion (Lutt and Tammik, 1992; Kask et al., 2003).

The role of wave action and its long-term changes in the coastal processes at the Lithuanian shores have not been properly quantified. However in the light of analogous studies performed for Estonia it is safe to say that the impact of wave-driven processes at the open Lithuanian sea coast is significant and can be largely amplified when it occurs in combination with the overall sea level rise or with local flooding.

The parameters of extreme storm waves occurring at the Klaipėda Seaport gate and propagating into Klaipėda Strait are estimated by Kriaučiunienė et al. (2006) for strong winds blowing from the western to north-western directions and for wind speeds of 15, 20 and 25 m/s. At the wind speed of 15 m/s, the height of the waves at the port entrance may reach about 3 m. For even stronger storms (wind speeds of 20 and 25 m/s), the wave height is expected to exceed 4 or 5 m, respectively.

These estimates match the wave data collected by visual observations in the Centre of Marine Research, Klaipėda. Yet, even larger waves may occur in this area. Historically, the roughest wave conditions were observed at the Lithuanian coast on 23 January 1962 when the wave height of 6 m was registered at Klaipėda. Such conditions were unexpectedly rough, because the south-western wind had a speed only about 20 m/s. During windstorm Gudrun in January 2005 the north-western wind reached 20 m/s in Palanga, but the wave height was only 4 m.

The possible effects of the changes in the wave regime in the entire Baltic Sea area are also poorly understood. In the Baltic Sea conditions, the knowledge of the wave height only is not enough for the coastal management. A variety of wave-induced processes, in particular, transport of sediments in the surf zone or the local wave set-up, largely depend on the wave height, length or period and the propagation direction. The experience from the Baltic Sea basin is that even the quantification of the role of ferry-induced waves required great efforts (Soomere et al., 2003; Parnell et al., 2008; Kurennoy et al., 2009) and the role of different wake parameters was still estimated with quite a large uncertainty (Paper IV).

Much of this uncertainty is caused by the shortage of the information about the real local wave regime. The long-term wave climate in open sea areas can be constructed from the long-term statistics of wave properties at the few existing measurement sites in the Baltic Proper (Soomere, 2008; Paper II). An attempt in this direction has been made with the use of the longest available instrumentally measured time series of wave properties at Almagrundet (Broman et al., 2006). The results of both numerical studies (Soomere, 2005a) and the analysis of historical wave data (Broman et al., 2006; Zaitseva-Pärnaste et al., 2009) confirm that the wave periods in the entire Baltic Sea are relatively small, usually 4–6 s.

The relatively short periods of natural waves and their moderate heights in the Baltic Sea are the key reason why waves from high-speed ferries serve as a potential marine hazard and/or source of energy pollution for the affected coastal sections. It is now widely accepted that heavy ship traffic has the potential of inflicting environmental damage to vulnerable areas such as wetlands or low-energy coasts, where wake-waves may cause extensive shoreline erosion or rapid changes to the coastal profile near the waterline (Parnell et al., 2007; Soomere et al., 2009), resuspend and transport bottom sediments, trigger ecological disturbance and harm the aquatic wildlife (e.g. Schoellhamer, 1996; Bourne, 2000; Parnell and Kofoed-Hansen, 2001; Osborne et al., 2007). These aspects are usually negligible on the open ocean coasts, but may become important in sheltered water bodies like the Baltic Sea or its sub-basins.

The introduction of powerful ships that are able to sail at high speeds in relatively shallow water created a new dimension of wave-induced hazards in the Baltic Sea conditions almost a century ago. The first adequately documented case of coastal hazard, which was caused by a ship in the open sea and led to loss of life, seems almost unbelievable. In 1912 in the Gulf of Finland, the Baltic Sea, a boy was washed from a wharf and drowned (Krylov, 2003). The wharf was 2.7 m above water level and was located at a distance of about 10 km from the sailing line of the warship Novik. The nonlinear wave height amplification, combined with extensive shoaling of long waves in shallow water, is the probable reason for this event (Soomere, 2007). There have been more recent similar events (Kofoed-Hansen and Mikkelsen, 1997; Hamer, 1999), resulting from the breaking of waves generated by fast ships.

The role of waves from fast ferries in coastal processes, which may be potentially substantial for medium-energy coasts under certain circumstances (Soomere and Kask, 2003; Levald and Valdmann, 2005; Erm and Soomere, 2006; Soomere, 2007), is poorly understood yet and needs further investigation. Early measurements typically show that the ship wave heights do not essentially exceed 1 m at depths of 3–5 m (Parnell and Kofoed-Hansen, 2001). These results have been obtained from a limited number of observations and contain relatively large uncertainties. Vessel wakes, however, have formed an appreciable portion of the total wave activity in Tallinn Bay since 1997. Their annual mean energy and its flux are, respectively, about 5–7% and 20–25% from that of the natural wave activity. The daily highest ship waves belong to the highest 1–5% of wind waves in this area (Soomere, 2005b).

The intense traffic of fast ferries, accompanied by high and long wake waves, at times approaching from a direction not common for wind waves, may stimulate sediment transport in the direction opposite to the natural littoral drift or current-induced transport of suspended matter during a relatively calm season. This effect was probably first mentioned by Elken and Soomere (2004) and has been quantified for one site at the coast of Tallinn Bay in Paper III.

Other major consequences of high, solitonic, vessel wakes are intense wave breaking and runup, and nonlinear interactions of solitonic waves (Peterson et al., 2003; Soomere, 2005b; Didenkulova et al., 2009). The research into this field, which is out of scope of this study, may also reveal some processes and effects associated with potential changes in wave properties (such as wave period and direction) in changing climatic conditions (Soomere et al., 2009).

1.4 Sea level changes

Sea level rise may enhance the magnitude of marine-induced hazards through a greater probability of the occurrence of extreme water levels and rise in wave energy at the shore, brought about by the increase in water depth, a consequent decrease in wave attenuation and a change in the boundary conditions at the coast. It is evident that the effect of the increasing probability of storm events is additionally amplified when high water levels are accompanied by large waves that affect the upper, usually unprotected shore sections. The overall potential changes to the nature of the coast may include the effect of landward migration of the extreme water level forming longer tidal channels, increasing the size of bays, creating new salt marshes, etc. It may also involve a change in the position of the deep water/shallow water demarcation line and consequently in wave refraction patterns (Pethick, 1992).

A rise in the sea level in combination with an increase in the frequency of extreme storm conditions, a quite possible scenario in the nearest future in the Baltic Sea basin (BACC, 2008), may cause considerable damage to the coastal area. An inevitable consequence of a large sea level rise will be a growth in wave energy in some parts of the coastal zone because of the weakening of the impact of refraction and nearshore wave breaking. Another, more subtle result is an accompanying increase in the wave run-up height on the coastal dikes and breakwaters, which may lead to coastal disasters. Although these effects are seldom registered on the coasts of the Baltic Sea, such damage to the dikes of Audru polder was observed after the January 2005 storm in Pärnu Bay, Estonia (Talts, 2006). Another example is a very strong storm of 2–5 December 1999 which almost completely damaged the new pier in Palanga, Lithuania (Žilinskas et al., 2000). It is, therefore, obvious that the long-term coastal management should account for the predicted sea level changes.

In the Baltic Sea, both sea level rise and lowering may cause serious problems (Johansson et al., 2004; Kont et al., 2003). Sea level rise may affect coastal urban infrastructures in various ways, including accelerated erosion and increased probability of coastal flooding. While flooding and its consequences are a general issue in coastal studies, wind-induced low water levels and effects caused by postglacial land uplift are not very frequent in other water bodies. Probably the largest inconvenience of low water levels in the coastal waters of Estonia and Lithuania is that ferry traffic may be stopped between the Estonian mainland and the Island of Hiiumaa. Another factor of extensive potential influence is the change in the properties of the variability of the local sea level (Johansson et al., 2001).

The state-of-art estimates for the rate of the global sea level rise for the 21st century range between 1.7 and 5 mm/year (IPCC, 2007). As the land is currently experiencing even faster uplift in the northern part of the Baltic Sea, the global sea level change is not dangerous for Finland or for the northern part of Sweden. In Estonia, the expected net sea level rise is quite small because of a similar uplift, the rate of which in the north-western part of Estonia is up to 2.8 mm/year (Zhelnin, 1966; Vallner et al., 1998), thus almost the same as the expected sea level rise according to many future scenarios (IPCC, 2007). The global seal level change will apparently balance or only weakly override the uplift there. Yet, in the southern Baltic Sea, e.g. along Polish (Zeidler, 1997) and Lithuanian coasts (that both experience slow downlift, Paper I), this rise will obviously cause problems within the coming decades.

A relatively rare threat, important in the northern parts of the Baltic Sea, is the postglacial net land uplift with respect to the mean water level. This process governs the long-term evolution of the mean sea level in most of Finland and around the Sea of Bothnia (Fig. 1.1). While around the Hanko Peninsula the water level has decreased by 30 cm during the last 100 years, the similar dropdown for the northern part of the Gulf of Bothnia exceeds 100 cm (Johansson et al., 2001). Land uplift leads to the necessity of more frequent dredging of harbours and waterways, or even to the relocation of the coastal infrastructure to ensure free access to the open sea. The economic estimates made in similar conditions in other parts of the ocean suggest that the countermeasures may be quite costly. For example, the costs of harbour and marina dredging in similar conditions are estimated as much as 7.6 million USD for Goderich Harbour and adjacent marinas only (Schwartz et al., 2004).

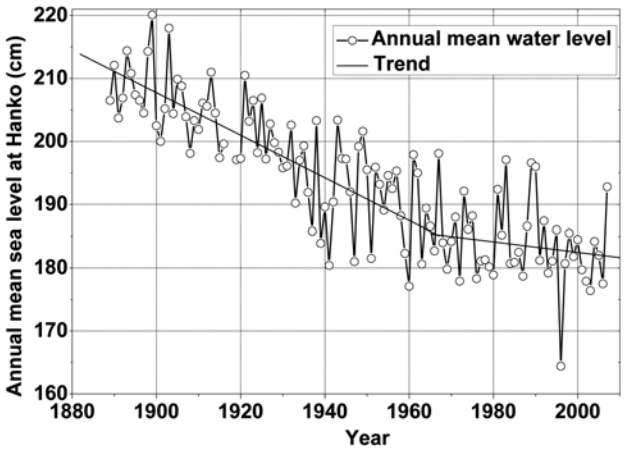

Fig. 1.2. Annual mean (solid line and circles) and fitted mean sea level (dashed line) at Hanko (Paper I)

An interesting feature is that the relative magnitude of land uplift along the northern coast of the Gulf of Finland has apparently changed around the year 1960 (Fig. 1.2). Relative uplift was about 3.3 mm/year until 1960 and has been about 1.6 mm/year since then (Johansson et al., 2004). This large shift in the uplift rate is evidently caused by both global sea level rise and increase in the local sea level owing to the overall intensification of westerly winds.

The situation is completely different at the Lithuanian coast. The entire coast of the southern part of the Baltic Sea generally experiences certain downlift. Combined with the increase in the global sea level, this process may result in large-scale adverse effects and loss of considerable amount of land in low-lying coastal sections. In particular, for the Lithuanian coasts the relative coast downlift is as large as about 2 mm/year (Dailidienė et al., 2004, 2006). During the last 100 years, the water level in Klaipėda Strait has risen by about 15 cm (Fig. 1.3). Much of this rise is concentrated between the years 1976 and 2005 when the average sea level increased by about 12 cm.

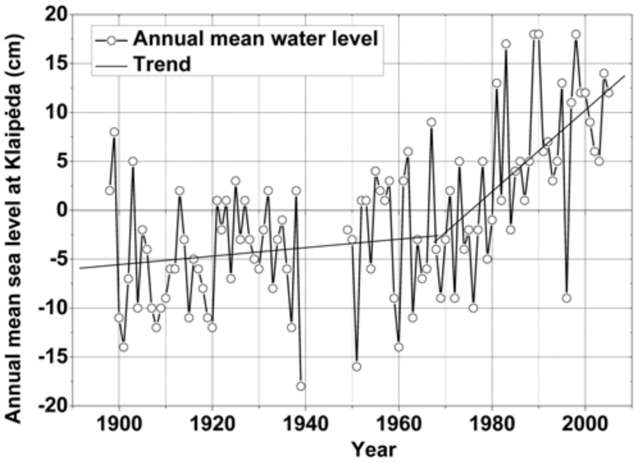

Fig. 1.3. Annual mean water level in Klaipėda Strait (Paper I)

This process may be additionally accelerated by frequent seasonal high water events. At the beginning of the 20th century, the maximum water levels along the Lithuanian coast usually occurred during the summer season (when wave activity has its annual minimum, Broman et al., 2006; Soomere and Zaitseva, 2007). For that reason, the high water level events only had a minor influence on coastal processes. The situation has changed by now: the maximum sea level values have frequently been reached during the winter season in the last few years. As this is the most active storm season, the combination of a high waver level and rough seas may considerably accelerate coastal erosion (Jarmalavičius and Žilinskas, 1996).

1.5 Increased risk of coastal flooding

An increase in storminess due the climate change, combined with either the overall water level changes or the increase in the probability of very high local water level, inevitably leads to an increase in the risk of another major marine hazard – coastal flooding. This risk is already high in several low-lying areas along the southern, eastern and north-eastern coasts of the Baltic Proper, and in certain sections of the coasts of the Gulf of Riga and Gulf of Finland.

An important feature which apparently has not been properly understood yet, is that increase in the flood risk is mostly connected with a substantial change in the distribution of different sea levels within the latter half-century. Considerable increase in the probability of the occurrence of high sea levels, first detected for the

Finnish coasts by Johansson et al. (2001), means that coastal flooding is expected to become more frequent and generally more devastating. A similar increase in the variability of sea level and frequent occurrence of high water has been recognized also for Estonian and Lithuanian coastlines. This tendency is obviously a generic source for coastal hazards for the entire eastern part of the Baltic Sea.

The most dramatic recent event in the area in question was windstorm Gudrun (Erwin). During that storm the all-time highest sea levels were recorded at all measurement sites along the southern coast of Finland and at many sites on the western and northern coasts of Estonia (Suursaar et al., 2006).

The high variability of sea levels and extreme single events have also been observed at Lithuanian sites (Dailidienė et al., 2006). The highest water level in Klaipėda Strait (186 cm over the long-term mean value on 17 October 1967) was nevertheless not exceeded. The reason for this is that the maximum wind speeds in hurricanes Anatol (04 December 1999) and Gudrun (09 January 2005) occurred far from Lithuanian coasts, and the highest water level (165 and 154 cm over the mean level, respectively) remained below the historical maximum.

There is clear evidence of an overall increase in the typical annual maximum sea level during the last decades of the 20th century. This phenomenon means that the probability of extensive coastal flooding has also increased considerably. An additional risk factor is the relatively fast water level rise during strong storms. For example, the sea level may rise at a rate of 20 cm an hour on the Lithuanian coast. The maximum water level is usually reached within 6–7 h (Dailiedienė et al., 2004).

1.6 Challenges to the management of the Baltic Sea coastal zone

The nature and properties of the majority of prime marine coastal hazards analysed in Paper I have been comprehensively studied in scientific literature. Yet, their appearance and damaging potential in the Baltic Sea conditions is not completely understood, as demonstrated by severe storms of November 2001 and January 2005 (Žilinskas et al., 2005; Suursaar et al., 2006; Soomere, 2008). A large part of the damaging potential and acting mechanisms are similar to those established for the open ocean coasts. For example, potential increase in wave heights is a widely studied issue in the North Atlantic (WASA, 1998; see also references in Broman et al., 2006).

There are, however, several marine coastal hazards that are either specific to the Baltic Sea or occur only in very limited sections of the coasts of the World Ocean. For example, changes in wave periods (that may lead e.g. to changes in the depth of closure or refraction patterns) or in the predominating wave directions are equally important for the functioning of the coasts. Great changes in these parameters are improbable on the open ocean coast in short-term run, but quite possible in the Baltic Sea basin (Soomere et al., 2009). While sea ice attacks (which only affect a few other coasts) may become less frequent owing to climate warming, the shortening of the ice season (Sooäär and Jaagus, 2007) will evidently lead to a considerable increase in the wave-induced loads on the coasts, because the winter season is the most windy one in the Baltic Sea (Mietus, 1998).

Changes in the wind regime are frequently considered only in the context of increasing storminess. Yet, changes in the wind direction or the translation speed of low pressure systems or modifications of the overall wind patters in strong storms are at times even more serious (Soomere et al., 2008a). In some cases, anthropogenic activity may also become evident in the form marine-induced coastal hazards. Wind farms, potentially affecting wind patterns and changing sea water mixing properties (Burchard et al., 2005), and wakes from fast ferries (Soomere, 2005a; Papers III, IV) are classical examples of this type.

The relative magnitude of many of the listed issues may change markedly when the local climate will be changed. As the coasts receive a large part of the energy of (changing) winds, they serve as a convenient "device" for early detection of the regional climate changes and shifts. The relevant analysis therefore has an extremely important role in foresight studies and long-term planning of coastal areas. An attempt to relate anthropogenic wave-induced hazards with the natural variations in local wave fields has been made in Paper III.

The complexity of the potential effects of wave energy may lead to different types of hazards to the nearshore, evolution of the coastline and functioning of the infrastructure at and in the vicinity of the coast. As the relative role of wave action in the coastal zone is rather high in the Baltic Sea basin compared with the open ocean coasts, any action planned in the coastal zone of the eastern Baltic Sea should be extensively scrutinised from the viewpoint of potential adverse changes to the wave properties (Papers I and III). This conjecture is in line with the overall understanding of experts that the planning of long-term coastal protection measures is a multi-faced problem, adequate and successful handling of which needs a lot of time, substantial material resources, extended knowledge of specific features of marine and coastal environment, and an art of unifying different views to the whole process (Kamphuis, 2000). However, this is the only way to handle many of the problems of coastal zone management effectively.

In conclusion, it is safe to say that, generally, extensive high-resolution information about the functioning of beaches, and dynamics and physics of marine hazards, combined with detailed cost-benefit analysis, form the prerequisite for sustainable development of coasts of any region. The most promising are the technologies that combine the detailed knowledge of small sections of the coast with the large-scale patterns of changes. They can provide resource managers with information regarding the local changes and spatial distributions of changing patterns that cannot be extracted from point measurements. Consequently, they allow for more informed decisions also with regard to preserving biodiversity and planning restoration efforts.

2 Wind wave fields on the eastern coast of the Baltic Sea

2.1 Introduction

Wave properties in the Baltic Sea are much less significant than in the open ocean in terms of extreme and typical wave heights and periods (Soomere, 2008). Still wave activity is the major driver of coastal processes along the eastern coast of the Baltic Sea and in many sections of its sub-basins. The Lithuanian sea coast is almost straight and exposed to the wind and wave impact. The Estonian coast, contrariwise, has a large number of semi-sheltered bays, the coasts of which are protected from relatively large waves that may occur in the Baltic Proper.

The basic properties of the northern Baltic Sea wave fields such as the typical and extreme wave heights and joint distributions of wave heights and periods, are fairly well known (Soomere, 2008). However, there is little and partially contradicting information about long-term changes in the wave properties in different parts of this water body and their possible effects.

The presentation in this chapter largely follows Paper II and focuses on the quantification of potential differences of the basic properties of wave fields and their long-term changes in the eastern part of the Baltic Sea. Section 2.2 discusses these aspects for the northern Baltic Proper based on the relevant information collected at Almagrundet (reflecting about 25 years of instrumental wave measurements near the western coast of the Baltic Proper) and a data set of visual wave observations from the Island of Vilsandi over 52 years. These two longest available wave records in this region allow deriving more or less reliable information about decadal and long-term variations in the wave climate.

The longest wave time series were collected in the eastern part of the Baltic Sea by the former USSR hydrometeorological service with the use of identical marine observation methods along the entire coastline of the USSR (Section 2.3). This accordance allowed a consistent comparison of the wave climate in different parts of the Baltic Proper. Wave observation points on the coast of Lithuania and the basic properties of the local wave climate are described in Section 2.4. Finally, similarities and differences in interannual and decadal variations in wave properties in the northern and southern parts of the eastern Baltic Proper are described in Section 2.5 based on wave data from Lithuania (1993–2005) and Estonia (Vilsandi, 1954–2005). The most intriguing question is whether long-term changes in wave activity have the same pattern in the entire Baltic Proper. Comparison of the above data sets with visually observed wave data in Lithuania suggests that the long-term trends in wave activity may be different in different parts of the Baltic Sea.

2.2 Wave fields in the Baltic Sea

The properties of wave fields of the Baltic Proper have been discussed in a number of recent studies based on instrumental measurements, numerical simulations and visual observations (e.g. Kahma et al., 2003; Jönsson et al., 2005, 2007; Broman et al., 2006; Soomere and Zaitseva, 2007; Alari et al., 2008; Cieślikiewicz and

Paplińska-Swerpel, 2008; Suursaar et al., 2009). The extremely complex shape and strongly anisotropic wind regime of the Baltic Sea (Soomere and Keevallik, 2001) suggest that its different parts may have largely different wave conditions (Soomere, 2003; Jönsson et al., 2005), whereas the highest wave activity is expected to occur on its eastern and north-eastern coasts.

The longest instrumental wave data set in the northern Baltic Sea (Almagrundet, 59°09'N, 19°08'E, 1978–2003) has been recorded with the use of upward-looking echo-sounders. As the measurement site is mostly open to waves coming from predominant storm directions, these wave data apparently characterize well the decadal changes in wave activity in the north-western area of the Baltic Proper (Broman et al., 2006).

Several shorter wave measurements have been performed in this area (Soomere, 2008). A non-directional waverider was operated in 1983–86 near Bogskär at 59°28'N, 20°21'E (Kahma et al., 2003). The wave properties were measured hourly during 14 630 h, which means, about 2 years of uninterrupted measurements. The measuring times were concentrated in the autumn season and thus well represent the wave climate during relatively windy months. A directional waverider has been operated since September 1996 in the open sea in the northern Baltic Proper (59°15'N, 21°00'E) during the ice-free seasons (Kahma et al., 2003). These data are the most representative of the Baltic Sea wave fields (Soomere, 2008); however, the data obtained since 2002 are neither published nor available for analysis.

There is a large pool of instrumental wave data from the sea areas close to Finland. For example, directional wave measurements in the Gulf of Finland in 1990–91, 1994 and from November 2001 (59°57.9'N, 25°14.1'E) during the ice-free seasons have considerably increased the awareness of wave conditions in semi-enclosed sub-basins of the Baltic Sea (Kahma and Pettersson, 1993; Pettersson, 2001; Kahma et al., 2003). Almost no instrumental wave data are available from the coastal areas of Estonia, Latvia and Lithuania where only sporadic measurements have been made with the use pressure-based sensors (Soomere, 2005; Alari et al., 2008).

The Swedish Meteorological and Hydrological Institute (SMHI) performed wave measurements at five locations around Sweden (southern Bothnian Sea, northern Baltic Proper, southern Baltic Proper, Kattegat and Skagerrak) during the years 2006–07. In the western Baltic Sea, wave measurements were made by the GKSS Research Centre and by the Bundesamt für Seeschifffahrt und Hydrographie (BSH) (Petterson and Hammarklint, 2008). These wave data cover the whole Baltic Sea, but represent a too short period to identify any changes in wave climate.

The measurements of wave properties in the north-eastern part of the Baltic Sea have for a long time supported the opinion that the significant wave heights hardly exceed 8–8.5 m in this water body. Wave conditions with a significant wave height over 7 m, which have occurred <10 times since 1978 (Soomere, 2008), can be interpreted as extreme situations.

There exists contradicting evidence of temporal changes in wave properties. A number of extremely rough wave conditions occurred during winter storms at the turn of the millennium in the Baltic Proper (Kahma et al., 2003), then in November 2001 in the Gulf of Finland (Soomere, 2005) and again in December 2004–January 2005 in the entire Baltic Sea (Suursaar et al., 2006; Soomere et al., 2008a). The extensive reaction of depositional shores to these events (Žilinskas et al., 2005; Eberhards et al., 2006; Tõnisson et al., 2008) underpinned the discussion as to whether the coastal processes in the Baltic Sea have become more intense than they were a few decades ago.

The available data suggest that changes in the Baltic Sea wave climate have been insignificant from the late 1950s until the early 1990s (Broman et al., 2006; Soomere and Zaitseva, 2007). The data series with the total duration of about 25 years at Almagrundet and 52 years at Vilsandi are long enough to extract climatological trends (WMO, 2001). The overall course of wave activity (Fig. 2.1) resembles a quasi-periodic variation, with an about 25-year interval between subsequent periods of high or low wave activity (Soomere, 2008). A rapid increase in wave intensity, 1.3–2.8% per year depending on the particular choice of the time interval and the site, is observed from the 1980s until the mid-1990s. This trend follows the analogous trends for the southern Baltic Sea, the North Atlantic (Bacon and Carter, 1991; Kushnir et al., 1997) and the North Sea (Gulev and Hasse, 1999; Vikebo et al., 2003). This overall increase in wave heights is consistent with the increase in wind speed over the northern Baltic Sea (Broman et al., 2006). This trend only existed for about 15 years and was replaced by a drastic decrease in the mean wave height since 1997 (Broman et al., 2006; Soomere and Zaitseva, 2007; Soomere, 2008).

Drastic changes in the mean wave height on the background of the gradual increase in the mean wind speed (Broman et al., 2006) suggest that the local wave generation conditions have substantially changed within relatively short time intervals. These changes are evidently not connected with a simple increase in storminess that was relatively high at the beginning of the 20th century, decreased in the middle of this century and then increased to the original level in the 1980s–90s in the Baltic Sea region (Alexandersson et al., 2000). The presented wave data (Fig. 2.1), however, suggest that these changes were not necessarily reflected in wave activity. On the contrary, wave conditions at Vilsandi and at Almagrundet were exceptionally calm in the 1980s. In particular, the overall wave activity was exceptionally high at Almagrundet in 1996–97, but the wind data from the Island of Utö (that well represent the open-sea wind conditions, Soomere, 2003) suggest that these years were relatively calm.

The decadal variations in the wave intensity at Vilsandi match well those at Almagrundet (Fig. 2.1). These measurement sites are both open to a large part of the predominant winds (Broman et al., 2006; Soomere and Zaitseva, 2007). The more or less coherent temporal behaviour of wave activity at these sites (Soomere, 2008) suggests that these variations adequately represent the overall changes in the wave regime and that they have the same pattern in the entire northern part of the Baltic Proper.

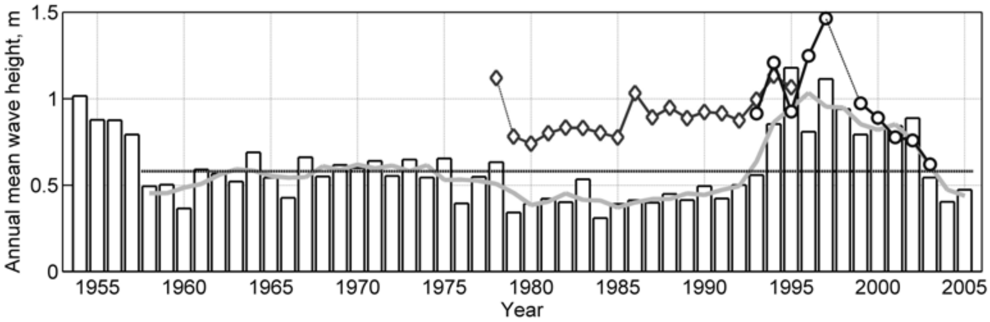

Fig. 2.1. The annual mean wave height at Vilsandi in 1954–2005 (bars, grey line: 3-year moving average since 1958) and at Almagrundet 1978–95 (diamonds) and 1993–2003 (circles). The horizontal line indicates the overall mean wave height at Vilsandi in 1958–2005 (Soomere, 2008)

The existing data, thus, lead to controversial conclusions about various aspects in changes in the wave climate in the Baltic Sea. As these changes have straightforward implications on the potential intensification of beach processes, there exists an obvious necessity to re-evaluate the basic features of temporal variability in wave properties along the coasts of the Baltic Proper. Another reason for such a study is that the changes in the wave climate have been found marginal, at least, until the mid-1990s in the southern Baltic Sea (WASA, 1995). Moreover, they are not reflected in several numerical hindcasts of the wave regime in the northern Baltic Sea (Räämet et al., 2009; Suursaar et al., 2009). This paradox suggests that the trends in the long-term average wave activity and extreme wave conditions may be different in different parts of the Baltic Sea. In order to shed some light on this matter, interannual and long-term variations of the annual mean wave height are compared for the northern Baltic Proper and for the south-eastern (Lithuanian) coast (Fig. 2.2) of the sea in Paper II.

An intriguing question is whether such mismatches between different 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. As the set of long-term wave data is fairly small in this area and evidently does not reproduce spatial variability in wave fields, numerical reproduction of the historical wave climate might be a feasible method to answer this question. Although contemporary wave models such as WAM and SWAN adequately restore the properties of wave fields in the Baltic Proper provided the wind information is correct (Tuomi et al., 1999), major problems have become evident in the reproduction of spatio-temporal patterns of wave fields (Räämet et al., 2009). The central source of uncertainties in estimates of the wave climate of the past apparently is the quality of marine wind data in the open Baltic Sea (Räämet et al., 2009). The situation seems to be better in semi-sheltered sea areas, which are only weakly affected by remote wave fields and where the wave properties rapidly follow the changes in the wind patterns, and for which high-quality marine wind data are available (Soomere, 2005a). For the listed reasons, analysis of long-term changes in the wave fields on the eastern coast of the Baltic Proper, presented in this chapter, is based only on measured and observed wave data. The relevant numerical analysis is performed for certain sections of Tallinn Bay in Chapter 3.

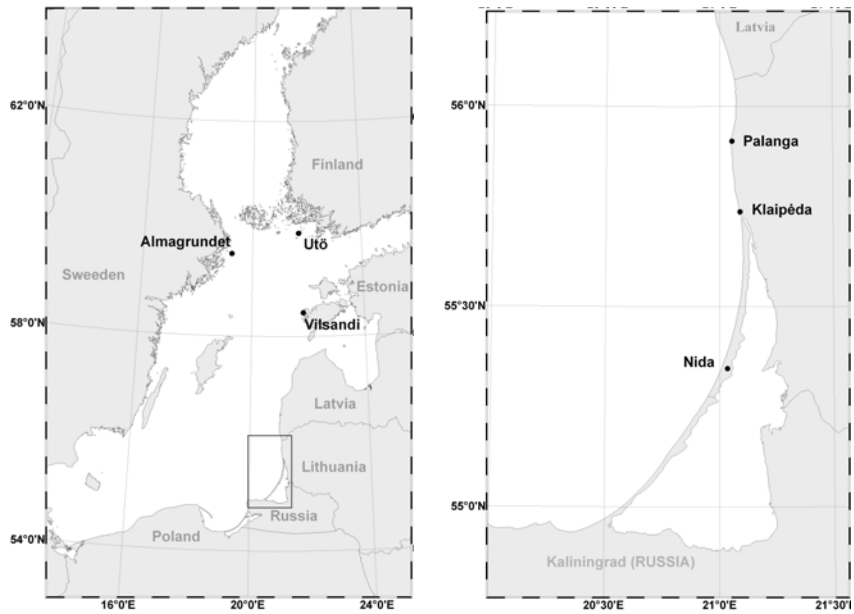

Fig. 2.2. Locations of long-term wave measurement and observation points in the northern Baltic Sea: (a) Baltic Proper; (b) Lithuanian coast. Grey squares show measurement stations operated by the BSH and black squares – the station operated by the SMHI and the Finnish Institute of Marine Research

2.3 Visual wave observations on the eastern coast of the Baltic Sea

The above has shown that a very limited amount of long-term instrumental wave measurements is available for the northern Baltic Proper and for the eastern coast of the Baltic Sea. For this reason, long-term visual wave observations form an important source of information about wave properties in the past. Regular wave observations along the eastern coast of the Baltic Proper were started in the middle of the 20th century in the framework of routine marine observations performed by the former USSR hydrometeorological service. Such observations (optionally performed using perspectometers, Soomere and Zaitseva, 2007) were undertaken in many locations using a standard procedure.

Although the number of observation sites and the selection of recorded parameters have decreased over the course of time, several sites have been operational almost permanently. Only a small fraction of data has been digitised and properly analysed. Data for 1954–2005 from Vilsandi (Fig. 2.2) are evidently the most representative of the north-eastern part of the Baltic Proper (Soomere and Zaitseva, 2007).

Visual observations from the coast have been frequently interpreted as representing only wave properties in the immediate vicinity of the observation point. Such data always contain elements of subjectivity and are not necessarily homogeneous in time. Usually they have poor spatial and temporal resolution (see, for example, Bacon and Carter, 1991). They inadequately characterise waves for offshore wind directions and may give a distorted impression of extreme wave conditions because of wave breaking and reflection in shallow water. Visual observations are, however, one of the few sources for detecting the wave climate and its long-term changes. Their basic advantage is the large temporal coverage.

A coastal site adequately reflecting the open sea wave conditions (except for easterly winds) is located at Vilsandi (Table 2.1, Fig. 2.2). Wave observations were performed there starting from 1954 up to three times a day depending on the duration of the daylight. The interval between subsequent observations is often much longer than the typical saturation time of rough seas in the northern Baltic Proper (about 8 h, Soomere, 2003) or the duration of wave storms (that seldom exceeds 10 h, Broman et al., 2006; Lopatukhin et al., 2006). Therefore, even the strongest storms, if they were not long enough or occurred during a night or were accompanied by low visibility, are not necessarily represented in the data set. Consequently, the observations cannot be used for the reconstruction of the time series of the sea state. Observation results (interpreted as regular samples of wave conditions at a site), however, often more or less adequately match the results of numerical simulations (Räämet et al., 2009). Since the number of single observations is quite large, the data were found to represent well 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).

2.4 Visual observations of wind waves in Lithuania

The Lithuanian coast is also generally favourable for adequate visual observations of wave properties. It is mostly straight (Fig. 2.2b) and hosts no substantial near-shore bedforms. The observed wave data usually reasonably reflect the open sea wave conditions in terms of wave periods, whereas the wave heights and propagation directions may be somewhat modified by shallow-water effects (Paper II).

Wave observations in Lithuania started soon after the establishment of the hydrometeorological station in Klaipėda in 1949 (Klimienė, 1999). Since the 1950s wave properties have been recorded at three observation points (Nida, Klaipėda and Šventoji, Fig. 2.2b, Table 2.1). The observation site at Šventoji was moved to Palanga in the mid-1970s. As the observing conditions, routine and the overall properties of the coast and the nearshore are very similar at these sites, this move probably did not cause any substantial inhomogeneity of the data set. The observation diaries and databases are now kept in the Centre of Marine Research (CMR) in Klaipėda.

Table 2.1. Wave measurement and observation sites

Site	Location	Observation method	Data coverage
Almagrundet	59°9'N, 19°8' E	Inverted echo-sounder	1977–2003
Vilsandi	58°23'N, 21°51'E	Visual observation	1954–2005
Nida	55°18'N, 21°0'E	Visual observation	1993–2005
Palanga	55°55'N, 21°3'E	Visual observation	1993–2005
Klaipėda	55°42'N, 21°7'E	Visual observation	1993–2005

The Palanga, Klaipėda and Vilsandi observation sites are fully open to the predominant wind directions (south-west and north-north-west), but are mostly sheltered from waves excited by eastern (offshore) winds. The geometry of the coastline at Nida permits proper observation of only properties of waves approaching from the western direction (from the west to north-north-west).

As the observer was located just a couple of metres above waterline at Vilsandi and the water depth at the wave observation point was about 4 m (Soomere and Zaitseva, 2007), waves higher than 4 m could not be adequately recorded at that site. At Nida, the observation point was located 7 m above the mean water level at the coast. The point at which the properties of waves were observed was about 700 m from the coastline at a water depth of 6–7 m (CMR, 1958; Klimienė, 1999). At Klaipėda, waves were observed from a site located about 3 m above the mean water level. The point at which wave properties were estimated lay about 500 m from the coastline.

At Palanga, observations were made from the pier, the surface of which is about 3 m above the water level and that extends to 470 m offshore. Waves were observed in a 6–7 m deep area. These circumstances made it possible to minimise shallow-water effects on the observed wave field and to use the bridge pillars as an additional fixed scale for estimates of the wave properties. As Palanga lies on an almost straight coastline, the directional extent of adequately observable waves is the largest of the Lithuanian sites and the wave data from this site are probably the most representative for the Lithuanian coastline (Klimiene, 1999).

Wave observations were only performed during daylight hours at the Lithuanian sites. The initial observation times in the 1950s and 1960s were 7:00, 13:00 and 19:00 Moscow time (GMT +3 h) (Gidrometeoizdat, 1985), which were later shifted to 6:00, 12:00 and 18:00 GMT according to the guidelines of the World Meteorological Organization (WMO, 2001). This shift seems to have no substantial impact on the quality and homogeneity of the data. A more detailed description of the observation routine is presented in Paper II.

The number of daily observations is usually different at Lithuanian stations and at Vilsandi during the winter season. The short duration of daylight allowed only one observation per day at Vilsandi while at Lithuanian stations almost always two sensible observations were made. Potential influence of this difference on the interpretation of long-term changes in wave activity is eliminated by using the daily mean wave height at all sites (Soomere and Zaitseva, 2007).

The available data set from Lithuanian observation stations for the years 1993–2005 (Table 2.1) contains information about the wave direction, maximum and mean wave heights and wave period. Wave periods were recorded only if they were at least 7 s. Since wave conditions with such periods form a clear minority of the Baltic Sea wave fields (Kahma et al., 2003; Broman et al., 2006; Soomere, 2008), they are not analysed in this study.

The frequency of different wave heights at Vilsandi resembles analogous distributions for wave heights in semi-sheltered bays such as Tallinn Bay (Soomere, 2005a). These distributions have a high percentage of almost calm situations that apparently correspond to offshore winds. Another (probably observer-specific) feature of visually measured wave data is that the percentage of wave heights slightly above 1 m, 1.5 m, etc. is considerably larger than the number of wave conditions slightly below these values (Soomere and Zaitseva, 2007). This peculiarity has frequently been recorded by older semi-visual observations of wind speed with the use of weather vanes (S. Keevallik, personal communication). It is to some extent visible in wave statistics from Palanga (Fig. 2.3) for wave heights around 1 and 2 m, but not in Nida data.

At Palanga, 0.25–0.5 m high waves are the most frequent (Fig. 2.3) and the entire distribution of wave heights resembles the analogous distributions in the open parts of the Baltic Sea (Soomere, 2008). Yet, a large fraction of (almost) calm situations evidently reflects the near-coastal conditions. As expected, based on the discussion of observation conditions at Klaipėda and Nida, the most frequent observations at these sites are almost calm conditions (wave heights below 0.25 m) as at Vilsandi.

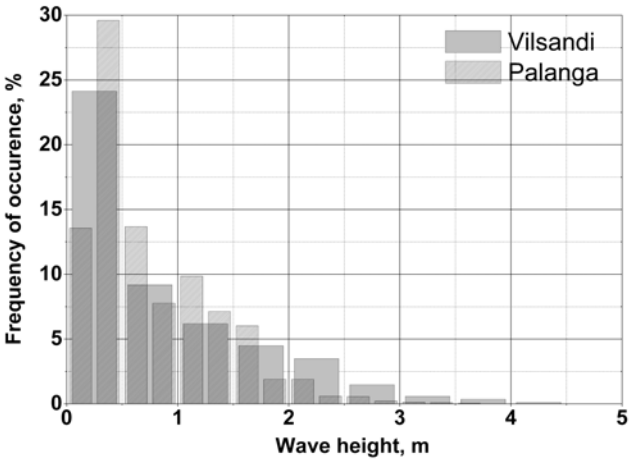

Fig. 2.3. Frequency of occurrence of waves of different heights (Paper II)

Relatively small waves (0–0.5 m) form almost a half of the observations at all Lithuanian sites, where the median wave height is close to 0.5 m as at Vilsandi. Waves 1–2 m in height also occur with an appreciable frequency (Fig. 2.3). Waves over 2 m form less than 5% of all observations. The distributions of the frequency of occurrence of different wave heights at Klaipėda and Nida are similar to those at Vilsandi. Their shape suggests that wave observations are generally reliable there.

The performed analysis of the observation conditions and basic features of wave data, therefore, suggests that visual wave observations from Lithuania represent relatively well the general features of the open sea wave fields and the basic properties of the wave climate in this part of the Baltic Proper, such as a moderate overall wave activity (with the annual mean wave height usually well below 1 m) and the presence of years with exceptionally low wave activity (the annual mean wave height as low as 0.4 m).

The interannual variations in the annual mean wave height are largely similar at all three Lithuanian observation sites. The overall mean wave height is the lowest at Nida (Fig. 2.4), probably because the coast at Nida is partially sheltered from the dominant south-western winds.

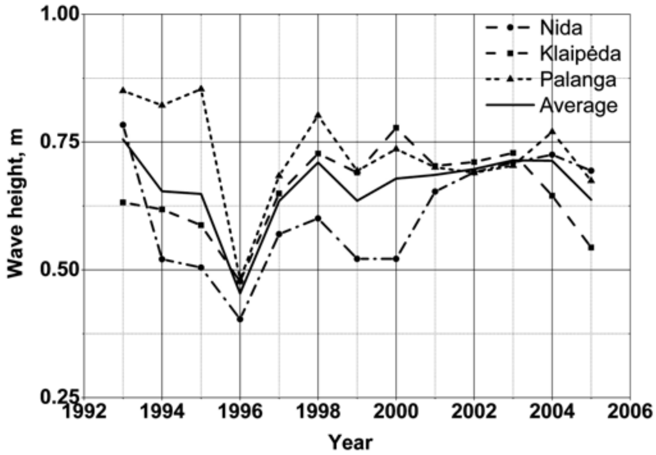

Fig. 2.4. The annual mean wave height at Klaipėda, Nida and Palanga and the average value for all stations (Paper II)

Short-term variations in wave conditions with the time scale of 1–3 years, the decreasing trend in wave heights in the mid-1990s and a slight increase at the turn of the millennium are basically similar for all stations. The calmest year was 1996 at all sites when the annual mean wave height was as low as 0.3 m at Nida. This coherence suggests that the site-specific changes and variations in wave intensity on the Lithuanian coast (with a total length of 90 km) are minor. Therefore, the wave regime along this coastal section can be reasonably characterized by average of wave properties from the three sites (Paper II).

2.5 Decadal variations in the eastern Baltic Sea wave fields

The digitised wave data set from Nida, Klaipėda and Palanga covers the years 1993–2005. This period contains a most interesting sub-period, 1998–2005, during which a rapid decrease in the annual mean height was observed in the northern sector of the Baltic Proper (Broman et al., 2006; Soomere and Zaitseva, 2007; Zaitseva-Pärnaste et al., 2009) after a considerable increase at the end of the 1980s and the beginning of the 1990s. The total variation in the annual mean wave height during the last two decades was almost fourfold at Vilsandi: from about 0.35 m in 1984 to 1.2 m in 1995 and then down to about 0.4 m in 2004 (Fig. 2.5). Similar variations in the annual mean wave height were also observed at Almagrundet where this quantity decreased from 1.45 m in 1997 to 0.625 m in 2003 (Broman et al., 2006). At the same time the average wind speed over the northern Baltic Proper gradually increased (Fig. 2.5).

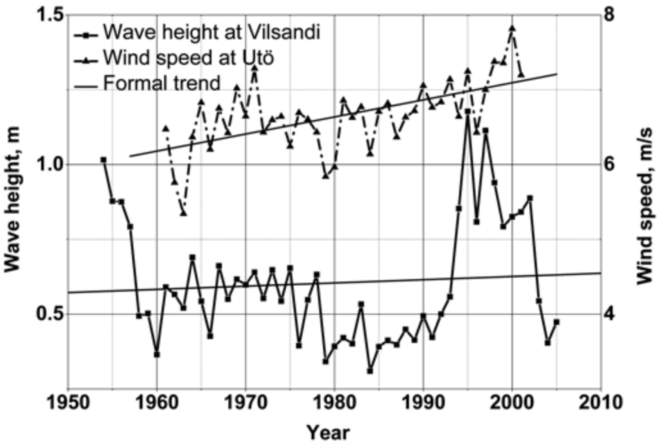

Fig. 2.5. Annual mean of wave height at Vilsandi and wind speed at Utö (Paper II)

A comparison of the annual mean wave heights (Fig. 2.6) shows that the overall course of wave activity in Lithuania and at Vilsandi and Almagrundet has some similarity in short timescales (1–3 years). For example, years with relatively low (e.g. 1996) and high (e.g. 1997–98) wave activity become evident at all sites in the mid-1990s.

The long-term variations in wave activity in the southern and northern parts of the Baltic Proper within the study period differ considerably. This difference becomes evident firstly in the overall pattern of changes in wave intensity and secondly in the form of opposite trends in the decadal and interannual wave activity.

Apart from the relatively low wave activity at the Lithuanian coast in 1996, no substantial changes in the average wave height occurred during the entire period of 1993–2005. On the other hand, the overall wave intensity in the northern Baltic Proper (at Vilsandi and Almagrundet) exhibits drastic variations (Fig. 2.6).

While a steep decrease (by up to 5 cm/year or about 10% on average) starting from 1997 is observed in the northern Baltic Proper, the linear trend for these years shows a slight (albeit statistically not significant) increase in the wave heights in

Lithuania. The overall trends of mean wave heights are therefore opposite in the southern and northern parts of the eastern coast of the Baltic Proper within the time period in question.

Another important difference in the long-term behaviour of wave properties in the northern and southern parts of the eastern Baltic Sea coast is that the annual mean wave height at the Lithuanian coast shows relatively low interannual variation. The fluctuations of the mean wave height in Lithuania are from about 0.45 m in 1996 to about 0.7 m in 1993–95 and 2003–04.

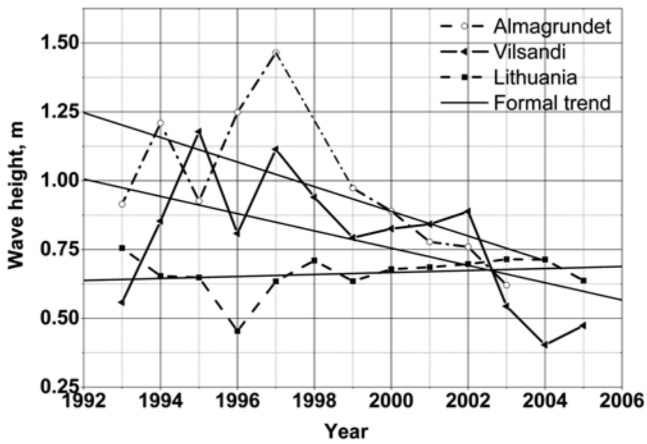

Fig. 2.6. Decadal variations in the annual mean wave height in the northern Baltic Proper and on the Lithuanian coast (Paper II)

The main outcome of the comparison of Vilsandi and Almagrundet data with those from the Lithuanian coast is that the basic properties of long-term variability and relevant trends in the overall wave height are very different in different parts of the Baltic Sea. The wave activity at the coasts of the northern Baltic Proper showed drastic variations in the 1990s and at the turn of the millennium (Broman et al., 2006; Soomere and Zaitseva, 2007), but did not change much at the eastern coast of the southern part of the Baltic Proper. The overall wave intensity decreases rapidly starting from about 1998 in the northern Baltic Proper, but only changes insignificantly at the Lithuanian coast, actually showing there a slight increase. Short-term (2–3 years) variations in the wave intensity, however, are more or less in phase at all sites.

3 Anthropogenic waves in Tallinn Bay

3.1 Introduction

Ship wake effects on the aquatic ecosystem and the coastal environment of inland waterways and low-energy, sheltered coasts have received considerable attention in the literature (Madekivi, 1993; Parnell and Kofoed-Hansen, 2001; Soomere, 2007). The increase in the number, speed and size of ships over the last decades has led to the situation where ship wakes may now be a significant driver of hydrodynamics on some coasts that are exposed to relatively high natural hydrodynamic loads. Such a situation was first identified a few years ago for several sections of Tallinn Bay (Soomere and Rannat, 2003; Soomere et al., 2003).

Generally, even a small increase in hydrodynamic loads may lead to a significant increase in sediment transport when the bed stress due to local factors is near a critical threshold for erosion or deposition (Talke and Stacey, 2003). The most significant effects and hazards associated with the increased hydrodynamic activity occur, however, when the leading ship waves are much longer than the typical wind waves (Soomere, 2005b). This is partially due to the fact that even relatively small levels of long-period wave energy can cause greater beach response than an equal amount of energy in the wind-wave frequencies (Coates and Hawkes, 1999).

In this Chapter, an attempt is made to estimate the contribution of ship-induced hydrodynamic activity to the overall budget of wave energy and its flux on a semi-sheltered, medium-energy beach. The presentation mostly follows Papers III and IV. Section 3.2 gives a short insight into the basic properties of the wave regime in the study area – almost tideless Tallinn Bay, one of the few places in the world where high-speed ferries frequently operate at near-critical speeds[2] close to the shoreline.

The setup of the relevant experiment towards measuring the properties and impact of wakes from high-speed ferries on a small beach on the south-western

[2] The characteristics of ship-generated waves are highly dependent on the depth Froude number $F_h = V/\sqrt{gh}$, where *V* is the ship's speed and *h* is the water depth. The speed at which $F_h = 1$ is called critical. Subcritical speeds are characterised by $F_h < 1$ and supercritical speeds by $F_h > 1$. The near-critical (also called transcritical) regime is defined as being where the vessel speed is within ±15% of the maximum phase speed $\sqrt{gh}$ of surface waves. Another important parameter of the sailing regime is the length Froude number $F_L = V/\sqrt{gL}$, where *L* is usually interpreted as the length of the ship's waterline. A specific regime called hump speed occurs when $F_L = 1/\sqrt{\pi} \approx 0.56$. Wave resistance is usually relatively high for $0.4 < F_L < 0.6$ and increases fast when $F_L \to 1/\sqrt{\pi}$. The highest waves eventually occur when the hump and the critical speed coincide (PIANC, 2003; Sorensen, 1973), which often happens for two ships (*SuperSeaCat* and *Nordic Jet*) operating in Tallinn Bay (Paper IV).

coast of Aegna at the entrance to Tallinn Bay (Fig. 3.1) in spring and summer 2008 is described in Section 3.3 together with the basic geomorphic features of the site. The major parameters of ship wakes characterising both explicit and implicit wave-induced coastal hazards and the magnitude of driving mechanisms of the coastal processes such as the daily maximum wave height (compared to extreme natural waves in this area) and the contribution of ship-generated wave energy and flux to the total wave energy and its flux, are depicted in Section 3.4. Section 3.5 presents the major features of the wind wave climate at the study site, estimated with the use of a triple-nested version of the WAM model. An estimate of the contribution of ship wakes to the existing wave energy and its flux and an analysis of the potential role of this contribution in the light of potential changes to the overall wind wave activity and owing to changes in the properties of ship wakes is presented in Section 3.6.

3.2 Fast ferry traffic in Tallinn Bay

Tallinn Bay is an almost non-tidal, semi-enclosed body of water, approximately 10 km×20 km in size, with the city of Tallinn located at its southern end. The bay belongs to a family of semi-sheltered bays that penetrate deep into the southern coast of the Gulf of Finland (Fig. 3.1). The overall hydrodynamic activity is fairly limited in this area (Alenius et al., 1998). There are, however, extensive water level variations driven primarily by weather systems, with a maximum recorded range of 2.42 m in Tallinn Bay. As very high (more than 1 m above the mean sea level) water level events are rare, the wind wave impact is concentrated into a relatively narrow range in the coastal zone.

The complex shape of the Baltic Sea and the anisotropy of predominant winds are the decisive factors of the local wave climate in Tallinn Bay. Most storms blow from the south-west but occasionally very strong north-north-west storms occur in the northern Baltic Proper and in the Gulf of Finland (Soomere and Keevallik, 2001, 2003). Long and high waves created in the Baltic Proper during south-western storms usually do not enter the Gulf of Finland owing to geometrical blocking (Caliskan and Valle-Levinson, 2008). Bottom refraction at the mouth of the Gulf of Finland may cause waves to enter the gulf under some circumstances (Soomere et al., 2008). However, on entering they keep propagating along the axis of the Gulf of Finland, and affect only very limited sections of the coast of Tallinn Bay, the northern part of which is additionally sheltered by the islands of Aegna and Naissaar (Fig. 3.2). The same is also true for waves excited in the Gulf of Finland by easterly winds. The roughest seas in Tallinn Bay occur during north-north-western storms that have a fetch length of the order of 100 km, and thus only produce relatively short waves (Soomere, 2005a). These features strongly limit the periods of wave components, the peak periods of which are usually well below 3 s, reaching 4–6 s in severe storms and only in exceptional cases exceeding 7–8 s.

As a result of these factors, the local wave climate is relatively mild in Tallinn Bay compared with the adjacent sea areas. The significant wave height exceeds

0.5–0.75 m in the bay with a probability of 10% and 1.0–1.5 m with a probability of 1% (Soomere, 2005a).

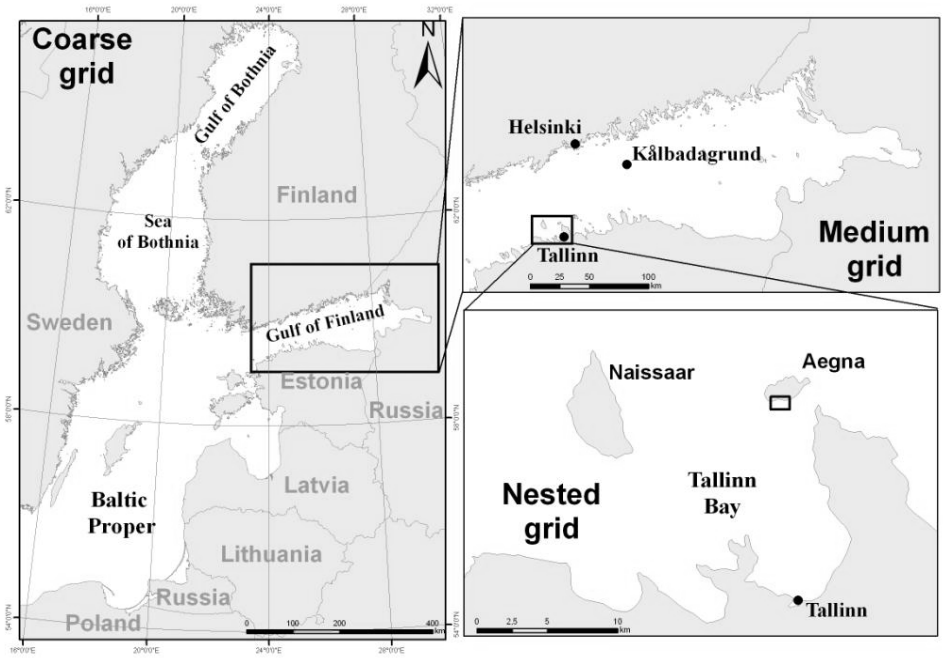

Fig. 3.1. Location scheme of the Baltic Sea, Tallinn Bay and nesting of the wave model

On the other hand, very high (albeit relatively short) waves occasionally occur during strong (north-)north-western winds, to which Tallinn Bay is fully open. The significant wave height typically exceeds 2 m at some time each year and may reach 4 m in extreme (north-)north-western storms in the central part of the bay. As a consequence, most of the coast of Tallinn Bay has preserved features indicative of periods of intense erosion (Lutt and Tammik, 1992; Kask et al., 2003) and as such it can be considered to be a medium-energy coastal environment. Detailed calculations of the parameters of the local wave climate have been performed for the nearshore of Pirita Beach (Soomere et al., 2008b). Similar calculations have been performed for the vicinity of the study site (see below) in Paper III.

A number of studies performed since 2001 have indicated that wakes from high-speed ferries may significantly contribute to hydrodynamic activity on the coasts of Tallinn Bay and may serve as a decisive aspect of planning and management of the coastal zone (Soomere et al., 2003; Levald and Valdmann, 2005; Soomere, 2005; Valdmann et al., 2006).

There have been significant changes in the types of high-speed vessels operating in Tallinn Bay during a few last years (Paper IV). A new generation of high-powered conventional ferries with service speeds of 25–30 knots (45–55 km/h) has replaced the older conventional ferries that sailed at 15–20 knots (25–

35 km/h). The properties of the wakes of these vessels were largely unknown until the relevant experiment described in Paper IV was undertaken near Aegna. Also, small hydrofoils have been replaced by much larger ships. As sailing lines have remained largely unchanged and no limitations have been imposed on the speed, the new ships may operate at near-critical speeds in areas where older ships were clearly subcritical.

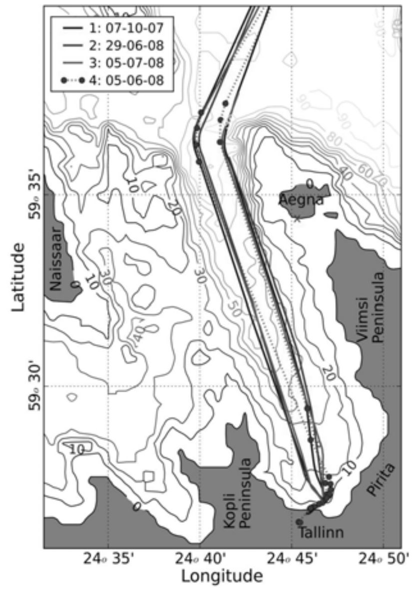

Fig. 3.2. Recorded sailing lines of four ferries in Tallinn Bay (Paper IV)

With these changes, the number of large vessels that are able to travel at near-critical speeds has almost doubled in Tallinn Bay since about the year 2000. The total number of departures of passenger ships from Tallinn to Helsinki was 22–25 per day in summer 2008 (Fig. 3.3). The decrease in the frequency of departures from a peak of around 35 per day in the early 2000s was mostly due to a significant reduction in the number of conventional ferry and hydrofoil crossings.

Although earlier studies have indicated or hypothesised that ship wakes may serve as a major driver of sediment transport at certain depths (Erm and Soomere, 2006) and directly or indirectly impact the coastal processes near the waterline (Soomere and Kask, 2003; Soomere, 2005; Osborne et al., 2007; Parnell et al., 2007), almost no unambiguous evidence existed about the impact of ship wakes on realistic medium-energy coasts until the experiment depicted in Paper IV was performed on Aegna.

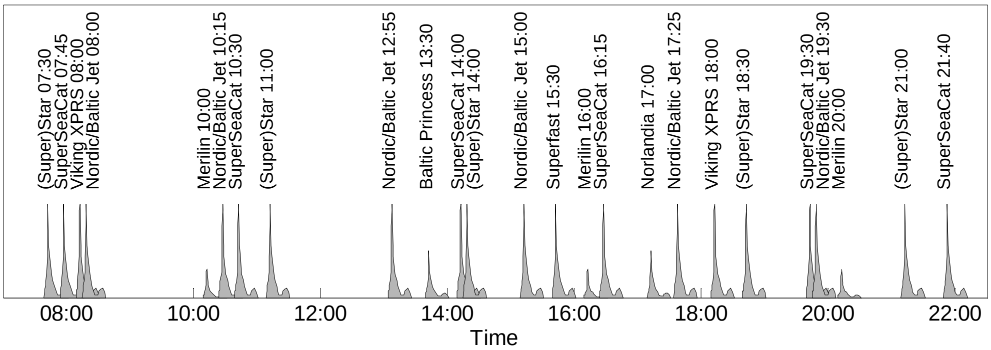

Fig. 3.3. Scheme of the timing, duration and relative height of wakes arriving at the study site generated by passenger ships travelling from Tallinn to Helsinki on weekdays in June–July 2008 according to the schedule (www.webmarine.ee) (Paper IV)

3.3 Experiment on Aegna

A series of experiments were undertaken in Tallinn Bay in the spring and summer of 2008 in order to update the information about hydrodynamic activity in Tallinn Bay caused by the new types of ships and to re-assess the properties of the wake waves in this bay based on systematic measurements over a longer time interval. A novel aspect of this study, details of which are out of the scope of this thesis, is an attempt to relate the properties of ship waves to their character and the resulting runup at the shoreline (Didenkulova et al., 2009).

The measurement site of ship waves was located on the south-western coast of Aegna, about 100 m offshore from a small semi-sheltered, mixed, gravel-sand beach immediately west of a jetty (Fig. 3.4, 59°34'15"N, 24°45'28"E). The island, about 1.5 km×2 km in size, is located 1.5 km north of the Viimsi Peninsula, at the northern entrance to Tallinn Bay. It is separated from the Viimsi Peninsula by a shallow-water (typical depth 1–1.5 m) channel with two small islands. Effectively, no wave energy enters Tallinn Bay from the east. The site, however, receives a relatively large amount of energy of wind waves entering Tallinn Bay during western and north-north-western storms.

The south-western coast of Aegna and the isobaths in its vicinity are predominantly (albeit not perfectly) oriented perpendicular to the ship wave rays (Fig. 3.4). The site is completely open to the wakes from ships sailing from Tallinn to Helsinki. It is, however, quite well sheltered from wakes of ships sailing to Tallinn and thus receives about a half of the total ship wave energy and flux.

In the vicinity of the study site, water depths increase over a short distance from the coast to approximately 2 m, beyond which there is a more or less linear slope from the position of the wave measurement device (Fig. 3.4) down to depths of 6–8 m and a gently sloping terrace 0.5–1 km wide to about 15 m water depth. This appearance of the sea bottom allows ship waves to propagate for a few tens of metres of the beach without breaking. The site, therefore, is appropriate for this study as it receives directly significant wave energy from vessels that may be operating in the near-critical regime (Torsvik et al., 2009). The waves apparently shoal to some extent before they arrive the measurement site but usually they only break at or very near to the shoreline, thus permitting measurement of the unbroken wave properties close to the shore and, in particular, obtaining adequate information about their energy and energy flux. This area has also been used as a study site in several previous studies (Soomere and Rannat, 2003; Erm and Soomere, 2006).

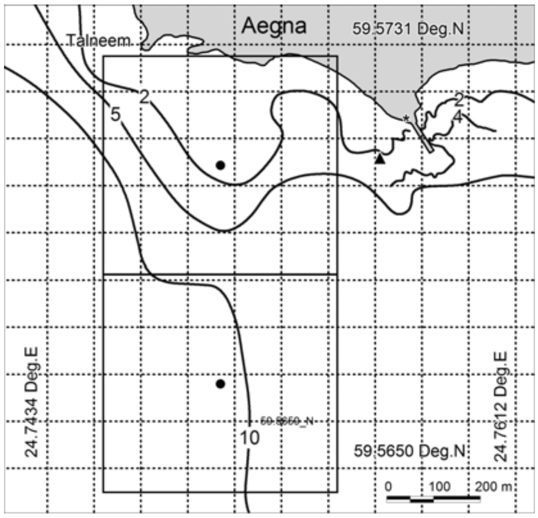

Fig. 3.4. The study site at the south-western coast of Aegna (right). The triangle shows the wave measurement site and the filled circles – the centroids of the grid cells of the wave model with the mean depth of 2 m and 7 m (called as 2 m site and 7 m site in what follows) (Paper III)

The ships mostly follow the same sailing line (Fig. 3.2). The typical distance from the study site to the sailing line was 2.5–3 km (Paper IV). There is evidence that that ships were frequently sailing in the near-critical regime over extensive sections of the route (Fig. 3.2, Torsvik et al., 2009).

The parameters of approaching vessel waves were measured by tracking sea-surface elevations of unbroken waves using an ultrasonic echosounder. The device was mounted on top of a heavy tripod, at a location about 100 m from the shore and 60 m from the southern end of the jetty (Fig. 3.1, 59º34.259'N, 24º45.363'E). The data were collected continuously over 30 days during the period from 21 June to 20 July 2008 at a recording frequency of 5 Hz.

As several wake events come in groups (due to the sailing times of the various ships, Fig. 3.3), each day usually has about 15 strong wake-wave events. These events, which occur at almost exactly the same time each day, are clearly distinguishable not only in the record of water surface, but also in the record of optical properties of sea water near the wave measurement site (see Paper IV). The total record contains more that 650 wake events, about 400 of which can be adequately separated from the wind wave background and attributed to particular vessels, and several hundred distinguishable smaller wakes. The typical duration of the identified single wake events varied from 15 to 20 min, depending on the particular ship, and reached 25–30 min in some cases. Events containing waves from two or more ships were even longer.

3.4 Data analysis

Single waves and their properties in each vessel wake were extracted with the use of both zero-upcrossing and zero-downcrossing methods of a properly smoothed recording of water surface elevations. The details of the procedure and a discussion of the reliability of the results are presented in Paper IV and in Kurennoy et al. (2009). To the first approximation, the maximum wave height is defined as the maximum of wave heights obtained by these two methods. This approach gives results which almost always coincide with the maximum variation in the water surface within 30 s intervals (Paper IV). The daily highest ship waves were compared with the calculated significant wave heights within the 3 h sections (see below, Section 3.5). In many cases combined wave systems from two vessels that arrived simultaneously resulted in the highest waves of the day.

The daily maxima of ship wave heights occurred exclusively for relatively long waves with periods of ~10 s or larger. They exceeded 1 m and were typically approximately 1.2 m (Fig. 3.5). The largest ship wave heights in generally calm conditions were 1.5 m. The combined ship and wind wave heights reached 1.7 m on a few days, with the significant height of the background about 0.3–0.5 m on those days (Paper IV). The lowest daily maxima correspond to weekends (Sunday, 6 July, and a weekend 19–20 July) when the number of ships is somewhat smaller and the loadings are likely to be less.

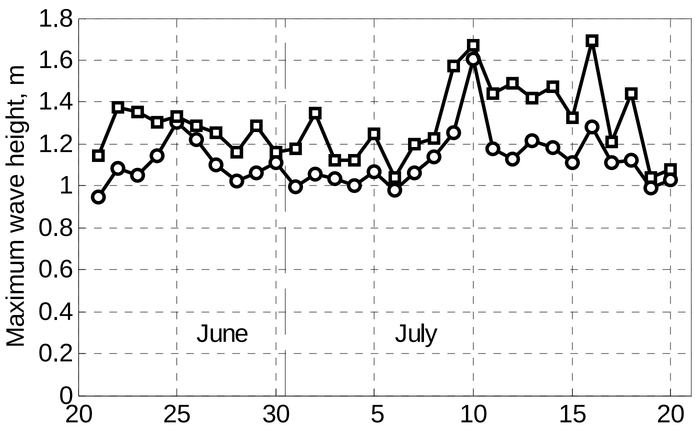

Fig. 3.5. Daily maximum ship wave heights. Squares reflect unfiltered data and circles – data filtered using a low-pass filter with a cut-off frequency at 0.4 Hz (Paper IV)

The highest waves measured in this study are significantly higher than the waves previously reported for Tallinn Bay (Soomere and Rannat, 2003). Assuming no loss or spreading of wave energy, a 1.08 m high wave with a period of 11 s, detected at Aegna in 2002 with the use of a pressure sensor at a depth of 6.7 m, would evolve to about a 1.3 m high wave at the location of the wave measurement device (Fig. 3.4), at a depth of about 2.7 m. In this light, several recorded wave heights exceeding 1.4 m suggest that the maximum ship wave heights have increased considerably since 2002.

The energy of each ship wake or a combined wake event is found from the long-wave energy spectrum of the wake calculated over the relevant manually selected section of the de-meaned and de-trended water surface record (Paper IV). While solely energy-based comparisons of waves of different origin are equivalent to a comparison of the squared wave heights, another key quantity – wave energy flux, frequently called wave power in coastal engineering applications – implicitly accounts for the wave periods since longer waves have larger group velocities. The energy flux caused by each ship wake is found by summing the energy flux of single waves in this wake separated from the relevant section of the water surface record based on the zero-upcrossing method (Paper IV; Kurennoy et al., 2009).

An accompanying study (Soomere et al., 2009) revealed that ship wakes strongly affected the beach at the study site. The reaction of the beach to the joint influence of wind and ship waves was quantified to some extent in terms of changes to the dry beach profile. The beach at the study site was stable under moderate wind wave conditions that gradually refilled it with sand and gravel overnight, whereas sediment was removed by vessel wakes during the day. Typically a small gravel berm of 15–30 cm height formed overnight under the impact of wind waves. This berm was usually completely removed by the first ship waves the following morning. On several calm days when ship-generated waves dominated, very rapid loss of sediment was observed (Soomere et al., 2009).

3.5 Comparison of wind waves and ship wakes at Aegna

Earlier estimates of the relative role of ship waves (Soomere, 2005b) were based on calculations of wind wave properties for the years 1981–2002. As described in Chapter 2, there have been significant variations in the overall wave intensity in the northern Baltic Sea basin over these years (Broman et al., 2006; Soomere and Zaitseva, 2007). The sea was comparatively calm at the end of the 1970s. A rapid increase in the annual mean wave height occurred from the mid-1980s until the mid-1990s (Fig. 2.1). This change lasted for about 15 years and has been reversed, with a significant decrease in the mean wave height, since 1997. By the year 2005, the annual mean wave height had decreased almost by a factor of three in the northern Baltic Sea from its peak (Soomere and Zaitseva, 2007).

The Gulf of Finland is open to the Baltic Proper and to waves excited by predominant westerly winds (Fig. 3.1). It is, therefore, natural to assume that the changes to the wave climate in the Gulf mirror those that happen in the Baltic Proper.

The substantial changes to the natural wave regime in recent years combined with the changes to the structure of the fleet suggest that there is a clear need to update estimates of the relative importance of wind and ship waves for coastal change and for coastal hazards. This update became possible based on the results of the above-described high-resolution measurements of properties of ship waves at Aegna in June–July 2008. The outcome, described in Paper III, serves as an example of the relevant studies of the role of vessel wakes in the development of a section of medium-energy coastline.

The wind wave climate in the vicinity of the study site is estimated with the use of a triple-nested version (Fig. 3.1) of the WAM model (Komen et al., 1994), the innermost model of which (grid step of about 1/4 nautical miles) allows an adequate description of nearshore wave properties, up to a depth of about 5 m and as close to the coast as about 200–300 m. Unlike from its earlier version (Soomere, 2005a), the improved model has as an extended frequency range (covering waves with periods down to about 0.5 s) and adequately represents the growth of a relatively short wave in low wind and short fetch conditions (Soomere et al., 2008b).

In order to construct a rapid estimate of the local wave climate, the wave calculations are split into a number of short independent sections. The method in use is based on two assumptions. Firstly, it is assumed that an instant wave field in Tallinn Bay is a function of a short section of wind dynamics. This is justified, provided wave fields rapidly become saturated and have a relatively short memory of wind history. In principle, this conjecture is a generalisation of the ideology of one-point wave models that are often in use even in the Baltic Proper where this assumption is only conditionally satisfied (Räämet et al., 2009; Suursaar et al., 2009; Zaitseva-Pärnaste et al., 2009). Secondly, it is implicitly assumed that remote wind conditions in the Baltic Proper insignificantly contribute to the local wave field. These assumptions are correct in Tallinn Bay for about 99.5% cases (Soomere, 2005a).

The model used wind data from 1981–2008 from Kalbådagrund (59º59'N, 25º36'E, Fig. 3.1). This is the only measurement site in the Gulf of Finland that correctly represents marine wind conditions (Keevallik, 2003). The output of the model is a time series of wave conditions (significant wave height, peak and mean period, propagation direction, etc.) for all 3 h periods. The presence of ice is ignored. As the mean number of ice days is 70–80 annually and, statistically, the ice cover is usually present during the windiest season, the computed mean parameters of wind waves are somewhat overestimated and represent average wave properties during the years with no extensive ice cover. The variations in wave properties were perfectly correlated for the 7 m and 2 m sites (Fig. 3.4, 3.6). This feature allows direct comparison of estimates obtained in Soomere and Rannat (2003) for a 6.7 m deep measurement site with the results of the current study.

During strong (north-)north-western and western storms, relatively high waves may penetrate into Tallinn Bay. The maximum significant wave height in the central part of this basin may reach 4.5 m in extreme storms (Soomere, 2005a). The model shows that the largest waves ($H_S = 3.02$ m) occurred at the study site on 19 November 1998 during a western storm with the wind speed exceeding 21 m/s over several hours. High waves, however, are infrequent in this area: $H_S > 1$ m occurs with a probability of <2% and $H_S > 2$ m with a probability of ~0.1% (Paper III). The typical daily highest ship waves (1.2 m), therefore, belong to the highest 2% of wind waves (Fig. 3.6). The weekly highest ship waves, with their height reaching 1.5 m at the site, belong to the highest 0.7% of wind waves. Such natural wave conditions occur, on average, only on two days each year.

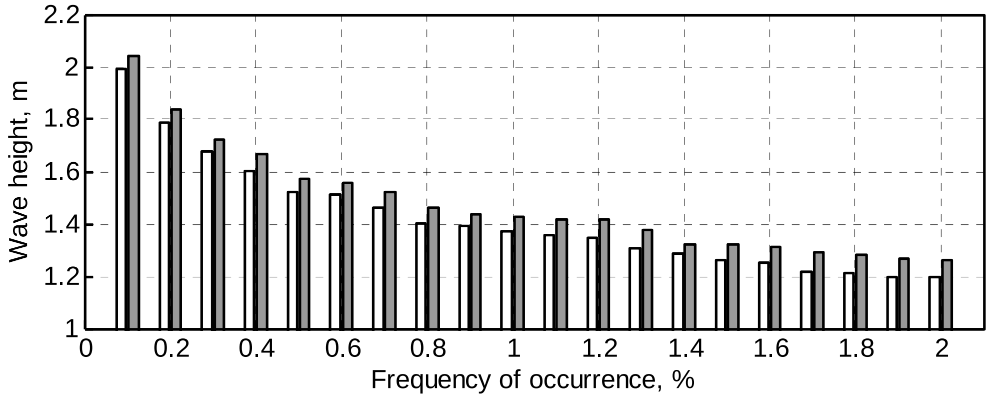

Fig. 3.6. Probabilities of occurrence of large significant wave heights near SW Aegna for 2 m water depth (white bars) and 7 m water depth (grey bars). Sites are shown in Fig. 3.4 (Paper III)

Quite surprisingly, unlike the situation in the Baltic Proper, interannual variations in the annual mean significant wind-wave height are fairly minor at the study site at Aegna (Fig. 3.7). While some variations in the annual mean wave height (for example, low wave heights in 1984, 1987 and 1991) are similar in Tallinn Bay and in the Baltic Proper, there is no evidence of increased wave heights in the late 1990s in Tallinn Bay.

The wave regime in Tallinn Bay is obviously almost insensitive to changes in winds blowing from the directions for which the wave field is strictly fetch-limited, that is, for winds from the east, south and south-west. Easterly winds are generally weak and infrequent in the entire Baltic Sea basin. As the bay is largely open to the western and north-north-western winds, these winds have eventually had no substantial changes between 1981 and 2008. The presented mismatch of the long-term behaviour of wind fields in the Baltic Proper and Tallinn Bay, therefore, suggests that essential changes in the wave regime in the Baltic Proper have been caused exclusively by changes in the properties of south-western winds, from which Tallinn Bay is sheltered. This conclusion, however, should be further validated on the basis of more realistic wind wave simulations for the entire Baltic Sea.

The annual mean wave height ranges between 36 and 50 cm at the 7 m site where the overall mean wave height is 43 cm. This estimate matches well with the estimates of the annual mean wave height of 59 cm in 1954–85 at the entrance to the Gulf of Finland (Zaitseva-Pärnaste et al., 2009).

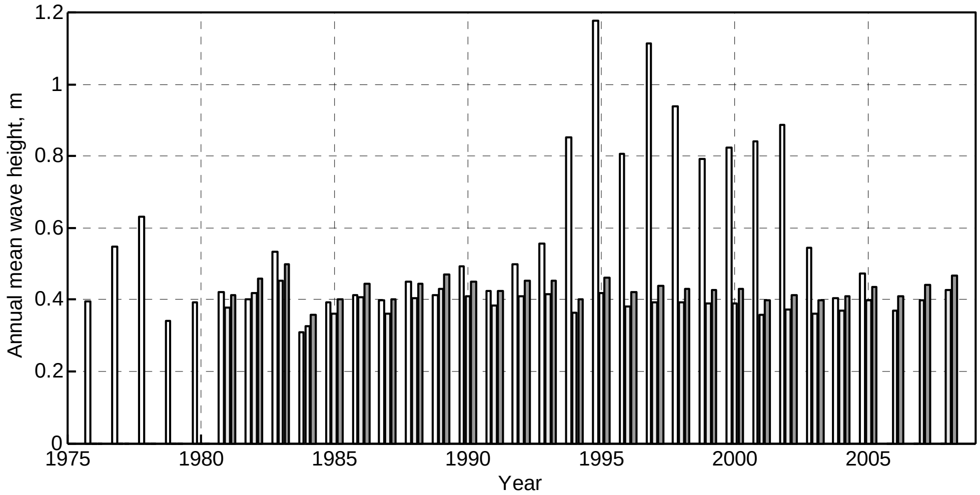

Fig. 3.7. Annual mean visually observed wave heights at Vilsandi (1976–2005, white bars, Soomere and Zaitseva, 2007) and modelled wave height at Aegna (1981–2008, light grey bars: 2 m site; dark grey bars: 7 m site) (Paper III)

Interannual variations in the mean wind-wave energy and its flux are somewhat larger. This feature is not unexpected, because the wave energy is proportional to the wave height squared, and the wave energy flux additionally accounts for the wave periods and is proportional to the wave height to the power of 2.5 for waves at the seaward border of the surf zone. The wind-wave energy density ranges between 80 and 230 J/m^2 (97–270 J/m^2) at the 2 m (7 m) site, and its flux is 300–800 W/m at the 2 m site. Note that in this study it is assumed, as in Soomere and Rannat (2003), that the wind-wave energy propagates with the group velocity of the wave corresponding to the spectral maximum. The overall mean energy density at the 2 m and 7 m sites is 143 and 169 J/m^2, respectively. The comparable ranges of variations in the energy and its flux suggest that larger wind waves do not necessarily have longer periods.

3.6 Ship wakes as energy pollution

The continuous recording of ship wake properties over almost a month (Paper IV) allowed derivation of reliable estimates of the contribution of vessel wakes to the overall wave activity at the study site. As shown above, the daily maximum heights of vessel wakes have increased considerably since the year 2000. Although the ships that produced the largest and longest waves in the past are no longer in service, the leading wave periods (10–13 s) and integral properties of vessel wakes such as the total wave energy and its flux have remained largely unchanged.

The wave regimes of the Baltic Sea and its sub-basins have pronounced seasonal variability (Soomere, 2005a; Soomere and Zaitseva, 2007). The monthly mean wave height varies up to three times in the Baltic Proper and typically by a factor of two in the coastal areas (Fig. 3.8). The corresponding variations in the wave energy and its flux are much larger. Therefore, the contribution of ship waves is the most important during the relatively calm period (April–August) which is also the biologically most active time and the spawning time of several fishes.

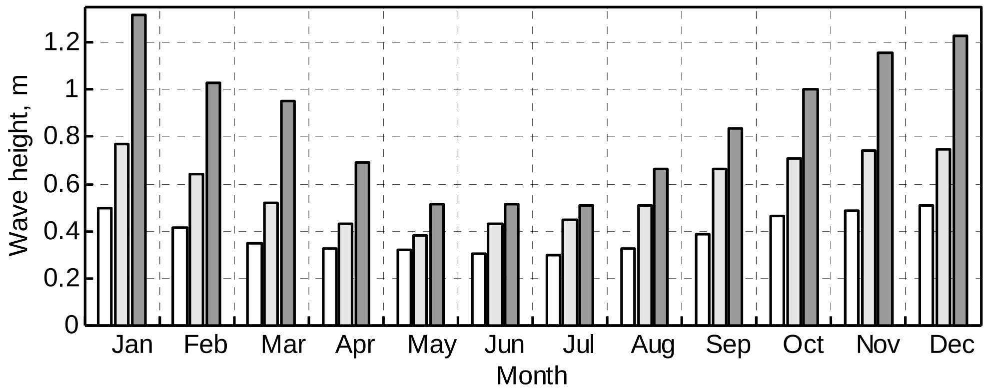

Fig. 3.8. Monthly mean wave height at Aegna (1981–2008, white bars), Vilsandi (1954–2005, light grey bars, Soomere and Zaitseva, 2007), and Almagrundet (1978–2003, dark grey bars, Broman et al., 2006) (Paper III)

In Paper IV it is demonstrated that the average mean vessel-wake energy density over the entire measurement cycle was about 16 J/m^2 in 2008. A comparison with the above values for the annual mean wind-wave energy density at the 2 m site shows that the contribution of vessel wakes at Aegna is about 10% in terms of the annual mean wave energy but up to 20% during relatively calm years. It is important to note, however, that the semi-sheltered study site only receives substantial wake energy from ships sailing in one direction, towards the open Gulf of Finland. The typical energy of wakes of ships sailing in the opposite direction, which reaches the study site, is about 10 times smaller (Kurennoy et al., 2009). A large part of this energy was recorded in earlier experiments (Soomere and Rannat, 2003). Therefore, the overall amount of ship wave energy received by the coast of NE Tallinn Bay definitely has not decreased since 2002 when the annual mean energy was estimated as 15.8 J/m^2 (Soomere and Rannat, 2003).

Unlike in Soomere and Rannat (2003), in this study the energy flux for ship wakes is calculated by summing this quantity carried by single waves. This method gives a much more exact estimate of the actual energy flux created by ship waves than earlier studies. The average vessel-wake energy flux was estimated to be about 70 W/m at the study site over the entire measurement cycle in 2008 (Paper IV).

This estimate was smaller than the value 110 W/m, derived in 2002–03 for a neighbouring site with a depth of 6.7 m (Soomere and Rannat, 2003). The difference may partially result from the changes to the fleet (Paper IV), with new ships tending to generate shorter waves, and thus contributing less to the energy flux. The more probable reasons, however, lie in the difference of the location of the study site in 2008 (that received only a small fraction of the energy flux created by waves sailing to Tallinn) and in the calculation methods. Earlier estimates assumed that the vessel wakes propagated with the group velocity of the wave with a weighted mean period of the wake (Soomere and Rannat, 2003). This assumption generally leads to underestimation of the role of the longest waves. Also, wave energy loss due to interaction with the bottom and spreading due to refraction when the waves propagate from the measurement site used in 2002 to the site in 2008 lead to a decrease of the estimate in Paper IV.

The average value of numerically simulated wind-wave energy flux over 1981–2008 at a depth of 2.7 m was 480 W/m (Paper III). At this site, the actually recorded part of vessel wakes contribute about 15% of the total energy flux and about 25% in relatively calm years. As the properties of waves from ships sailing in opposite directions usually differ insignificantly (Torsvik et al., 2009), this contribution may be almost twice as large for coastal sections that are open to wakes from all ships. During the calm season, the energy flux due to vessel wakes is about 1/3 of the wind-wave energy flux (Fig. 3.9). As the intensity of many beach processes (such as sediment transport in the surf zone) are determined by the energy flux, the impact of vessel wakes may become decisive on some sections of the coast.

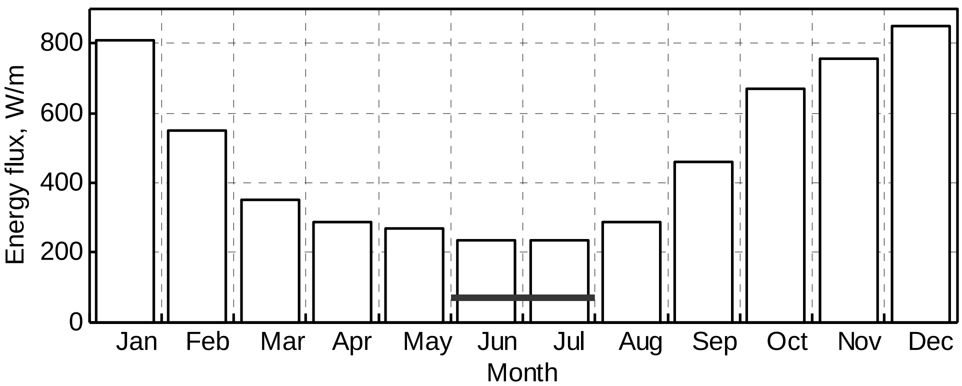

Fig. 3.9. Average density of wind-wave energy flux at Aegna (1981–2008). The horizontal line shows the average density of vessel-wave energy flux (70 W/m) in summer 2008 (Paper III)

The analysis, thus, shows that vessel wakes can significantly contribute to the energy budget of medium-energy shorelines, especially during relatively calm periods. Although this contribution is relatively small (~10%) in terms of the energy budget, it is substantial in terms of the highest waves and energy flux, especially during summer months.

The frequent presence of high and long vessel waves (the equivalent of which occurs under natural conditions very infrequently in some water bodies) and their unusually high runup (Didenkulova et al., 2009) generally need response in impacted areas, either in terms of coastal protection or warnings for the users of the nearshore or the beach (PIANC, 2003). The role of ship traffic may even be decisive to geomorphic changes on some sections of the beach (Soomere et al., 2009). These aspects suggest that the excess hydrodynamic activity produced by high vessel wakes may exceed the tolerance level in some areas adjacent to fairways. In such cases, it should be interpreted as a specific type of pollution (Stumbo et al., 1999).

Conclusions

Summary of the results

Although surface waves are one of the main driving forces of coastal processes and shallow-water marine ecosystems in the World Ocean, their role is especially important in micro-tidal water bodies like the Baltic Sea. While several classical marine-induced hazards to the coastal zone such as tsunamis are immaterial in the Baltic Sea basin, potential changes to sea level, wave regime and wind-induced coastal flooding can significantly affect the coastal communities even when the relevant forecasts are timely and ways of mitigation of the consequences of marine hazards have been planned.

In the Baltic Sea area, both sea level increase and decrease may cause substantial problems. The potential effects of sea level rise and storm surges on coastal processes and urban infrastructures (such as coastal flooding and its consequences) are well understood. The effects of wind-induced low water levels and effects caused by postglacial land uplift are infrequent in other water bodies.

A specific potential hazard in relatively large, complex-shaped water bodies such as the Baltic Sea is the potential changes in the surface wave regime. Apart from changes in the wave heights, equally important for the functioning of the coasts are the changes in wave periods and in predominating wave directions. Great changes in these parameters are improbable for open ocean coasts, but quite possible in the Baltic Sea basin. They may occur, for example, owing to changes in the wind direction or the translation speed of low pressure systems.

The introduction of powerful ships that are able to sail at high speeds in relatively shallow water has created a new dimension of anthropogenic pressure and wave-induced hazards in the conditions of the Baltic Sea and similar water bodies. Direct threats are caused by nonlinear wave height amplification, combined with extensive shoaling and dangerous breaking of long waves in shallow water. There is, however, indirect potential damage to the ecosystem and the coasts by vessel waves that are much longer than wind waves and at times approach from directions not common for wind waves. They may stimulate sediment transport in the direction opposite to the one created by natural factors.

As the coasts receive a large part of the energy of (changing) winds, changes in the coasts serve as a convenient “device” for early detection of the changes and shifts in the local climate. The relevant analysis therefore has an extremely important role in foresight studies and long-term planning of coastal areas.

Similarly to records of visual wave observations at Vilsandi, visually collected data represent relatively well the general features of the open sea wave fields on the Lithuanian coast. An interesting difference in the temporal behaviour of wind wave activity has been detected for the eastern coast of the Baltic Sea. While the changes in wave activity have the same pattern in the entire northern part of the Baltic Proper, the basic properties of the interannual and decadal variability and relevant trends in the overall wave height are very different in different parts of the eastern

Baltic Sea. While the annual mean wave height in the northern Baltic Proper showed drastic variations at the turn of the millennium, it did not change much in the southern part of the Baltic Proper. There is also dissimilarity in the trends in wave activity in different parts of the Baltic Proper and gradual increase in the average wind speed. This feature suggests that certain nontrivial changes in the wind patterns have occurred in the area in question.

Vessel wakes form an even increasing anthropogenic load to the coastal zone. There have been significant changes in the types of high-speed vessels. In particular, new high-powered ferries with service speeds of 25–30 knots operate now in Tallinn Bay. The new ships may operate at near-critical speeds in areas where older ships were clearly subcritical.

The continuous recording of ship wake properties over almost a month in summer 2008 allowed the derivation of reliable estimates of the contribution of vessel wakes to the overall wave activity at the entrance to Tallinn Bay about 3 km from a fairway. The daily maximum heights of vessel wakes have increased considerably since 2000 and are now in the range of 1.2–1.5 m in calm conditions on the south-western coast of the Island of Aegna. Although the ships that produced the largest and longest waves in the past are no longer in service, the leading wave periods (10–13 s) and integral properties of vessel wakes such as the total wave energy and its flux have remained largely unchanged in this area.

An intriguing result of the wind wave modelling is that there has been no substantial change in the overall wind wave intensity in Tallinn Bay despite significant changes in the Baltic Proper since the 1980s. This feature suggests that no great changes have occurred in the properties of the western and north-western winds in the sea areas surrounding Tallinn Bay, because the properties of wave fields excited by other wind directions are strictly fetch-limited in this bay and thus almost entirely defined by the local wind speed. This result also indicates that the increase in storminess in the Baltic Sea area not necessarily compensates the impact of the new, anthropogenic component of local hydrodynamic activity.

The vessel wakes contribute significantly to the energy budget of shorelines during relatively calm periods. Although this contribution is comparatively small (~10%) in terms of the energy, it is substantial in terms of the highest waves and energy flux. The frequent presence of high vessel waves (the equivalent of which occurs under natural conditions very infrequently in many semi-sheltered basins) generally needs response in impacted areas, either in terms of coastal protection or warnings for the users of the nearshore or the beach.

Main conclusions proposed to defend

1. Various marine-induced hazards are analysed in the conditions of the eastern coast of the Baltic Sea. The role of surface waves is especially important in micro-tidal water bodies like the Baltic Sea, whereas some classical marine-induced hazards to the coastal zone such as tsunamis, are immaterial in this basin.
2. In addition to changes in the wave heights, the changes in wave periods and in the predominating propagation direction are equally important for the functioning of the coasts. Great changes in these parameters are improbable for the open ocean coast, but quite possible in the Baltic Sea basin.
3. Visual wave observations from the Lithuanian coast represent relatively well the main properties of the wave climate in this area, such as a moderate overall wave activity and the presence of exceptionally calm years.
4. Short-term (2–3 years) interannual variations in wave intensity mostly occur simultaneously on the entire eastern coast of the Baltic Sea.
5. The basic properties of decadal variability and relevant trends in the overall wave height are very different in different parts of the Baltic Sea. The annual mean wave height (that showed drastic variations at the turn of the millennium in the northern Baltic Proper) did not change much on the Lithuanian coast in 1993–2005.
6. Analysis of in situ measured vessel wake properties at the entrance to Tallinn Bay on the south-western coast of the Island of Aegna in June–July 2008 revealed that their daily maximum heights are 1.2–1.5 m and have increased considerably since the beginning of the decade.
7. The leading wave periods (10–13 s) and integral properties of vessel wakes (the total wave energy and its flux) have largely remained unchanged in this area despite substantial changes in the fleet.
8. Vessel wakes continue to contribute significantly to the energy and energy flux at the south-western coast of Aegna, and potentially at many other medium-energy shorelines.
9. There has been no substantial change in the overall wind wave intensity over 1981–2008 in Tallinn Bay despite significant changes occurring in the Baltic Proper. Therefore, increasing storminess in the Baltic Sea basin not necessarily compensates the continuing anthropogenic pressure to semi-sheltered, medium-energy beaches like the study site in Tallinn Bay.
10. The extra hydrodynamic activity caused by high-speed vessels can be interpreted as a specific type of systematic pollution.

Perspectives for future work

The analysis in Paper I revealed that several marine coastal hazards and drivers of coastal processes are either specific to the Baltic Sea or similar water bodies, or are decisive only in very limited sections of the coasts of the World Ocean. A generic example of this kind is the field of surface waves, which is usually characterised in terms of (changes to) wave heights, energy or energy flux. However, equally important from the viewpoint of coastal processes and coastal engineering solutions are the changes in wave periods (that may lead, e.g., to changes in the depth of closure) or in wave propagation directions. Differently from the open ocean conditions, quite small changes in the wind regime in enclosed basins (for example, changes in the wind direction leading to an increase in the fetch length) may produce great changes in these parameters. Such changes are interesting in themselves and obviously important for many applications. Remarkably, their impact can be studied with the use of vessel wakes as a well-defined test signal. These waves often have periods differing from those of typical wind waves and they frequently approach from directions that are sheltered from wind waves.

The analysis above also confirmed that, in some cases, the anthropogenic pressure may also become evident as a specific marine-induced coastal hazard. Their relative magnitude may change considerably when the local climate will be changed. As the coasts receive a large part of the energy submitted to the surface layers by different forcing factors, the monitoring of the coasts serves as a convenient method for early detection of the changes and shifts in the local climate. The relevant measurements and their interpretation have an extremely important role in foresight studies and long-term planning of coastal areas.

Although one cannot restore the exact course of wave properties over time from wave data obtained visually in hydrometeorological stations because of the low temporal resolution of the observations and their intrinsic uncertainties, these observations have been found to reflect satisfactorily the basic properties of the wave climate and its changes in the Baltic Sea basin. The dissimilarity of the trends in the overall wave activity in the southern and northern parts of the Baltic Proper, combined with the mismatch of the temporal trends in wave heights and the overall gradual increase in the average wind speed in the area, suggests that the climate changes in the area in question may become evident in very different forms. Further examination of historical wave data from different regions of the sea may shed some light on the spatial patterns of changes in the wave regime in the Baltic Sea region.

The continuing high level of ship wave activity in Tallinn Bay and in similar sea areas means that there remains a concern about the potential impact of ship wakes on vulnerable coasts. The vessel wakes contribute significantly to the energy budget of shorelines during relatively calm periods. Although this contribution is relatively small in terms of the energy budget, it is substantial in terms of the highest waves and energy flux. The role of ship traffic may even be decisive in terms of geomorphic changes on some sections of the beach (Soomere et al., 2009).

The frequent presence of high vessel generated waves (the equivalent of which occurs very infrequently under natural conditions) and their unusually high runup (Didenkulova et al., 2009) generally need response in impacted areas, either in terms of coastal protection or warnings for the users of the nearshore or the beach (PIANC, 2003). On many sea coasts the presence of such high and steep, soliton-like waves, which are accompanied by significant beach run-up is believed to be an additional agent of coastal erosion even if they have periods of only about 7 s and occur only twice a day (Velegrakis et al., 2007).

On the other hand, the regular presence of such high wakes occasionally containing strongly asymmetric components may be used to understand the sediment transport induced by transient wave trains, which is an important driver of the morphology and evolution of the coastline. Most of the research in this field is focused on the net transport due to a large number of waves. Much less is known about sediment transport due to a single wave or a short wave group. Since the long wave components of ship waves arrive at the shore as a group of a few waves, this approach enables the study of the impact of virtually single waves on sediment transport processes (including net and bulk bedload transport of sediments by single wakes) in the coastal zone.

The continuing increase in the intensity of ship traffic may easily lead to the situation in which the excess hydrodynamic activity in coastal areas affected by high vessel wakes becomes intolerable. In the light of the United Nations Convention on the Law of the Sea (UNCLOS), ship wakes should be interpreted as a specific type of pollution in such cases (Stumbo et al., 1999). This feature should be addressed in the analysis of the impact of harbours and associated ship traffic in the neighbourhood of vulnerable areas.

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Papers constituting the thesis

Paper I Valdmann, A., Käärd, A., **Kelpšaitė, L.,** Kurennoy, D., Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica*, **21**(1-2), 3–12.

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

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Abstract

The thesis focuses on the analysis of spatio-temporal changes in the properties of wind waves on the eastern coast of the Baltic Sea in the context of marine-induced coastal hazards. Another central topic is the contribution of vessel wakes to the overall hydrodynamic activity under changing properties of the local wave regime.
Major marine hazards affecting the northern and eastern coasts of the Baltic Sea are reviewed first. While several classical hazards such as tsunamis are immaterial here, changes and variability in sea level, wave regime and wind- and wave-induced coastal flooding have the largest impact on coastal environments and communities in this region. Recent advances in the analysis, and quantification of the influence of the natural factors and their changes in different Baltic Sea regions are described. The role of changes in the sea level and wave climate and various wave-induced hazards in the coastal zone (including those of anthropogenic origin) are discussed in detail in the Baltic Sea context together with the ways of the mitigation of their consequences.

Changes in the wind wave climate in the eastern Baltic Sea for 1993–2005 are detected by means of comparison of historical, long-term visual wave observations in Lithuania and Estonia and wave measurements in the northern Baltic Proper. The basic properties of interannual and decadal variability and relevant trends in the overall wave height are very different in different parts of the Baltic Sea: while the annual mean wave height in the northern Baltic Proper showed drastic variations at the turn of the millennium, it did not change much at the eastern coast of the southern part of the Baltic Proper. Also, there have been no substantial changes to the overall wind wave intensity between 1981 and 2008 in Tallinn Bay despite very significant changes occurring in the Baltic Proper. At the same time, short-term (2–3 years) variations in the wave intensity are mostly in phase along the entire eastern coast of the Baltic Sea.

The role of frequent vessel wakes in the wave energy budget of semi-sheltered beaches has been re-evaluated for the Tallinn Bay conditions. The daily maximum heights of vessel wakes have increased considerably since the beginning of the decade, while the leading wave periods (10–13 s) and integral properties of vessel wakes such as the total wave energy and its flux have largely remained unchanged. The typical daily largest ship waves (1.2–1.4 m) are equivalent to the annual highest 0.8–1.8% of wind waves and the highest ship waves (1.7 m) to the highest 0.25% of wind waves. Vessel wakes contribute about 10% in terms of wave energy and 25% in terms of energy flux. This anthropogenic contribution is not compensated by a natural increase in local hydrodynamic activity in Tallinn Bay. Substantial seasonal variation in the natural wave intensity with markedly low wind waves in the biologically most active season suggests that vessel wakes may play a decisive role during some seasons even in areas with overall high wind wave activity and on medium-energy coasts. The extra hydrodynamic activity caused by vessel wakes can be interpreted as a specific type of pollution in a marine system.

Resümee

Väitekiri keskendub Läänemere idaranniku lainetuse tingimuste ajalis-ruumilise muutlikkuse kvantifitseerimisele merelt lähtuvate ohtude kontekstis. Teine keskne aspekt on kohaliku loodusliku lainetuse režiimi võimalike muutustega kaasnev laevalainete osakaalu muutumine üksikutes rannaosades.

Esitatakse süstemaatiline ülevaade merelt lähtuvatest ohtudest Läänemere idaranniku tingimustes Leedu ja Eesti randade näitel. Mitmed avaookeani randades domineerivad ohufaktorid (nt. tsunami) ei tekita siin arvestatavat ohtu. Kõnesolevad rannad on aga suhteliselt tundlikud veetaseme tõusu, lainetuse omaduste muutuste ja tormiajude tugevnemise suhtes, mis võivad ohustada rannikuvööndi ökosüsteemi ning põhjustada olulist materiaalset kahju. Näidatakse, et nende tegurite (eriti veetaseme ja lainekliima muutuste) muutumine ja mõju on erinev mere erinevates osades. Detailselt vaadeldakse veetaseme tõusu ja lainekliima muutustega kaasnevaid ohtusid Läänemerel, võimalusi nende leevendamiseks ning nende poolt tekitatud kahjude minimeerimiseks.

Analüüsitakse lainekliima muutusi ajavahemikul 1993–2005 Läänemere idaranniku erinevates osades visuaalsete vaatluste andmestike alusel ja ning võrreldakse neid Läänemere avaosa põhjapoolses sektoris toiminud muutustega. Lainetuse tingimuste suhteliselt lühiajalised muutused (mastaabiga 2–3 aastat) on toimunud põhiosas sünkroonselt kogu Läänemere idarannikul. Seevastu ligikaudu 10-aastase ajamastaabiga muutused on Leedu ja Eesti rannikul täiesti erinevad. Aasta keskmine lainekõrgus varieerus 1993–2005 Läänemere avaosa põhjapoolses sektoris mitmekordselt, kuid Leedu rannikul olid muutused mõnekümne protsendi piires. Samuti erinevad oluliselt aasta keskmise lainekõrguse trendid Leedu ja Eesti läänerannikutel. Suured erinevused esinevad ka Eesti ranniku erinevates osades: Saaremaa rannikul varieerus aasta keskmine lainekõrgus 1981–2008 mitmekordselt, kuid Tallinna lahes on muutused olnud tagasihoidlikud.

Esitatakse täpsustatud hinnangud laevalainete võimaliku osakaalu jaoks Läänemere poolsuletud lahtedes Tallinna lahe näitel 2008.a. suvel läbi viidud ulatuslike välitööde ja tuulelainete modelleerimise alusel. Laevalainete maksimaalne kõrgus Aegna muuli lähistel on alates 2000. aastast märgatavalt kasvanud, kuid kõrgeimate lainete perioodid (10–13 s), laevalainete energia ja energia voog on sajandivahetusega samal tasemel. Päeva kõrgeimad laevalained (1.2–1.4 m) on ekvivalentsed 0.8–1.8% kõrgeimate looduslike lainetega ning kogu mõõtesessiooni kõrgeimad laevalained (1.7 m) – ligikaudu 0.25% kõrgeimate tuulelainetega. Laevalainete energia moodustab ligikaudu 10% looduslike lainete energiast ning laevalainete energia voog 25% tuulelainete energia voost. Kuna tuulelainete intensiivsus Tallinna lahes pole viimasel kolmel aastakümnel märgatavalt muutunud, moodustavad laevalained endiselt märgatava osa hüdrodünaamilisest koormusest. Loodusliku lainetuse intensiivsuse sesoonse varieerumise tõttu võivad laevalained vaiksetel kuudel kujuneda domineerivaks hüdrodünaamiliseks koormuseks isegi suhteliselt suure keskmise lainekoormusega rannaosades, mistõttu laevalaineid on loogiline vaadelda kohaliku ökosüsteemi jaoks kohati ohtliku energiareostusena.

Abstraktas

Disertacijoje yra nagrinėjami bangų savybių pokyčiai rytinėje Baltijos jūros dalyje ir apžvelgiami pavojai, kurie gali kilti dėl šių pokyčių.

Kadangi Baltijos jūroje klasikinių jūrinių pavojų, tokių kaip cunamis, tikimybė yra maža, vandens lygio, bangų klimato pokyčiai gali sukelti reikšmingą poveikį pakrantės aplinkai ir žmonėms. Darbe aprašyti naujausi duomenys apie bangų stebėjimus šiaurinėje ir rytinėje Baltijos jūros dalyje, taip pat atlikta esamų duomenų analizė. Remiantis gautais duomenimis įvertinamas galimas skirtingos prigimties bangų (natūralių ir antropogeninių) poveikis priekrantei.

Vėjo bangų klimato pokyčiai rytinėje Baltijos jūros dalyje 1993–2005 metais yra nagrinėjami lyginant istorinius, ilgalaikius bangų stebėjimus Lietuvoje ir Estijoje. Taip pat remiamasi bangų matavimais šiaurinėje Baltijos jūros dalyje. Atvirose Baltijos jūros dalyse nagrinėjamo laikotarpio metu banginės savybės, vidutinės metinės bangų aukščių vertės ženkliai kito, tačiau tuo pačiu laikotarpiu vėjo bangų parametrai Talino įlankoje nesikeitė. Trumpalaikiai, 2-3 metų, bangų intensyvumo svyravimai yra beveik vienodi ties visa rytine Baltijos jūros pakrante.

Laivų sukeltų bangų įtaka bendrai bangų energijai pusiau uždarose įlankose buvo įvertinta remiantis Talino įlankos pavyzdžiais. Nors maksimalus laivų bangų aukštis per paskutinius dešimt metų padidėjo, tačiau pagrindinis šių bangų periodas (10–13 s) ir netiesinės savybės, tokios kaip bangų energija ir energijos srautas, liko nepakitę. Maksimalus dienos laivų sukeltų bangų aukštis (1.2–1.4 m) atitinka 0.8–1.8% maksimalių metinių vėjo bangų. Laivų bangų įnašas į bendrą bangų energijos biudžetą sudaro 10%, ir atitinkamai į energijos srautą - 25%. Antropogeninių bangų poveikis nėra kompensuojamas natūralių bangų aktyvumo augimu Talino įlankoje. Be to, sezoninis vėjo bangų intensyvumo svyravimas su pastebimai sumažėjusiu intensyvumu biologiškai aktyviu laikotarpiu leidžia teigti, jog laivų bangos gali būti laikomos specifine jūrinės ekosistemos tarša.

Appendix A: Curriculum Vitae

1. Personal data

Name	Loreta Kelpšaitė
Date and place of birth	11.10.1979, Rokiškis, Lithuania
Citizenship	Lithuanian

2. Contact information

Address	Ehitajate tee 43-80, 12618, Tallinn, Estonia
Phone	(+372) 55950058
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3. Education

Educational institution	Graduation year	Education (field of study/degree)
Vilnius University	2005	Physics (environmental and chemical) / MSc
Šiauliai University	2003	Physics / BA

4. Language skills (fluent; average, or basic skills)

Language	Level
Lithuanian	native language
English	fluent
Russian	fluent
Italian	basic skills

5. Further training

Period	Educational or other institution
Mar. 2009	Statistical software for climate research, Malta
Mar. 2008	Summer school on environmental dynamics climate forcing and global patterns, Venice, Italy
Sept. 2007	2D Hydrodynamic Flow & Transport with SMS, Salt Lake City, Utah, USA
Aug. 2007 – Sept. 2007	Summer School "Waves and Coastal Processes", Tallinn, Estonia
Oct. 2006	International Networking of Young Scientists "Marine environment protection and nature conservation", Tallinn, Estonia
Apr. 2006	ALARM GIS training course for beginners, Leipzig, Germany
Dec. 2005	ASI course on advanced modeling techniques for rapid diagnosis and assessment of CBRN agent effects on water resources, Istambul, Turkey.
Jan. – June 2002	University of Modena and Reggio Emilia, Italy.

6. Professional employment

Period	Organisation	Position
2007 – to date	Institute of Cybernetics, Tallinn University of Technology	Extraordinary researcher
2006 – 2007	CORPI, Klaipeda University	Assistant

7. Scientific work

Conference presentations

10th International Coastal Symposium, Lisbon, Portugal, "Energy pollution: the relative influence of wind-wave and vessel-wake energy: Tallinn Bay, the Baltic Sea" (2009).

"Sea and coastal research 2009", Nida, Lithuania, "Estimation of wave induced sediment transport at Aega Island, Tallinn Bay" (2009).

Interdisciplinary workshop "Effects of climate change: coastal systems, policy implications, and the role of statistics" of Marie Curie networks SEAMOCS, Malta, "Energy pollution: The relative influence of wind-waves and vessel-wake energy in Tallinn Bay, Baltic Sea" (2009).

SEAMOCS network meeting and conference on fatigue, Oslo, Norway, "Wave regime changes at the Baltic Sea Eastern coast" (2008).

3rd Regional Student Conference "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Juodkrantė, Lithuania, "Wave regime variations at the Lithuanian coast of the Baltic Sea" (2008).

The International Conference (school-seminar) on the Dynamics of Coastal Zone of Non-tidal Seas, Baltiysk, Russia, "Value of the depth of closure at the different Lithuanian sea coast points" (2008).

US/EU-Baltic 2008 International Symposium “Ocean Observations, Ecosystem – Based Management & Forecasting”, Tallinn, Estonia, “Wave climate variability in the Tallinn Area” (2008).

"Sea and coastal research 2008", Palanga, Lithuania, "Closure depth at the Lithuanian coast" (2008).

2nd Regional Student Conference "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Klaipėda, Lithuania, “Waves regime near the Lithuanian sea coast” (2006).

International student conference "Aplinka ir pasaulis", Šiauliai, Lithuania, "Numerical modeling of currents dynamics by the Lithuanian sea coast" (2006).

36th national Lithuanian physics conference, Vilnius, Lithuania, "Currents structure in the Baltic sea near the Lithuanian coast" (2005).

Regional Student Conference "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Palanga, Lithuania, "Oil spill from the D6 numerical modeling" (2004).

Organized Conference:

3rd International Student Conference "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Juodkrantė, Lithuania 9–13 October 2008

Articles indexed by ISI Web of Science

Valdmann, A., Käärd, A., **Kelpšaitė, L.,** Kurennoy, D., Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica*, **21**(1-2), 3–12.

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

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

Peer-reviewed articles in other international research journals

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

Articles published in conference proceedings

Soomere, T., Zaitseva, I., **Kelpsaite, L.** 2008. Mismatch of trends of average wave activity and extreme wave conditions in the northern Baltic Sea, *Geophysical Research Abstracts*, **10**, Paper 04128, 2008 (Proc. European Geosciences Union (EGU) General Assembly, Vienna, 13–18 April 2008), CD, 4 pp.

8. Defended theses

MSc thesis "Currents dynamics in the Baltic sea, near Lithuanian coast" (2005).
Bachelor thesis "Transport waves in semiconductors" (2003).

9. Main areas of scientific work and current research topics

Waves and coastal processes for engineering applications, nonlinear interaction and mathematical simulation.

10. Honours and awards

Marie Curie Fellow, 2007–2009;
Socrates/Erasmus Fellow, 2002.

Appendix B: Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Loreta Kelpšaitė
Sünniaeg ja -koht	11.10.1979, Rokiškis, Leedu
Kodakondsus	Leedu

2. Kontaktandmed

Aadress	Ehitajate tee 43-80, 12618, Tallinn, Estonia
Telefon	(+372) 55950058
E-posti aadress	loreta@cs.ioc.ee

3. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala/kraad)
Vilniuse Ülikool	2005	Füüsika (keskkonnafüüsika ja keemiline füüsika); magister
Šiauliai Ülikool	2003	Füüsika; bakalaureus

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

Keel	Tase
Leedu	emakeel
Inglise	kõrgtase
Vene	kõrgtase
Itaalia	algtase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija ja nimetus
Märts 2009	Statistilised meetodid kliimauuringutes, Malta
Märts 2008	Rahvusvaheline suvekool: keskkonna dünaamika, kliimamuutuste mõjutegurid ja globaalsed mustrid Veneetsia, Itaalia
September 2007	Kahemõõtmelise hüdrodünaamika ja transpordi modelleerimine, Salt Lake City, Utah, USA
August 2007 – September 2007	Suvekool "Lained ja rannikuprotsessid", Tallinn
Oktoober 2006	Rahvusvahelise noorte teadlaste võrgustik (INYS) "Merekeskkonna ja looduse kaitse", Tallinn
Aprill 2006	ALARM GIS koolitus algajatele, Leipzig, Germany
Detsember 2005	NATO ASI kursus veevarude diagnoosi modelleerimise kaasaegsete meetodite alal, Istambul, Türgi
Jaanuar – juuni 2002	Modena ja Reggio Emilia Ülikool, Itaalia, üliõpilane

6. Teenistuskäik

Töötamise aeg	Tööandja	Ametikoht
2007 – praeguseni	Tallinna Tehnikaülikooli Küberneetika Instituut	Erakorraline teadur
2006 –2007	CORPI, Klaipeda Ülikool	assistent

7. Teadustegevus

Konverentsiettekanded

X rahvusvaheline rannikuteaduse sümpoosium, Lissabon, Portugal, "Energy pollution: the relative influence of wind-wave and vessel-wake energy: Tallinn Bay, the Baltic Sea" (2009).

"Sea and coastal research 2009", Nida, Lithuania, "Estimation of wave induced sediment transport at Aega Island, Tallinn Bay" (2009).

Rahvusvaheline konverents "Effects of climate change: coastal systems, policy implications, and the role of statistics", Marie Curie võrgustik SEAMOCS, Malta, "Energy pollution: The relative influence of wind-waves and vessel-wake energy in Tallinn Bay, Baltic Sea" (2009).

Marie Curie võrgustiku SEAMOCS koosolek ja teaduskonverents konstruktsioonide väsimuse alal, Oslo, Norra, "Wave regime changes at the Baltic Sea Eastern coast" (2008).

III regionaalne üliõpilaskonverents "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Juodkrantė, Leedu, "Wave regime variations at the Lithuanian coast of the Baltic Sea" (2008).

Rahvusvaheline rannikuvööndi dünaamika konverents (suvekool-seminar), Baltiisk, Venemaa, "Value of the depth of closure at the different Lithuanian sea coast points" (2008).

US/EU ja Baltimaade rahvusvaheline sümpoosium “Ocean Observations, Ecosystem –Based Management & Forecasting”, Tallinn, Estonia, “Wave climate variability in the Tallinn Area” (2008).

"Sea and coastal research 2008", Palanga, Leedu, "Closure depth at the Lithuanian coast" (2008).

II regionaalne üliõpilaskonverents "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Klaipėda, Leedu, “Waves regime near the Lithuanian sea coast” (2006).

Rahvusvaheline üliõpilaskonverents "Aplinka ir pasaulis", Šiauliai, Lithuania, "Numerical modeling of currents dynamics by the Lithuanian sea coast" (2006).

XXXVI Leedu füüsikakonverents, Vilnius, Leedu, "Currents structure in the Baltic sea near the Lithuanian coast" (2005).

Regionaalne üliõpilaskonverents "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Palanga, Lithuania, "Oil spill from the D6 numerical modeling" (2004).

Korraldatud konverents:

III regionaalne üliõpilaskonverents "Biodiversity and functioning of aquatic ecosystems in the Baltic Sea region", Juodkrantė, Leedu, 9–13 oktoober 2008.

Artiklid, mis on indekseeritud ISI Web of Science andmebaasis (1.1)

Valdmann, A., Käärd, A., **Kelpšaitė, L.,** Kurennoy, D., Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica*, **21**(1-2), 3–12.

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

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

Teaduslikud publikatsioonid rahvusvahelistes eelretsenseeritud ajakirjades (1.2)

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

Avaldatud konverentsiettekannete tekstid

Soomere, T., Zaitseva, I., **Kelpsaite, L.** 2008. Mismatch of trends of average wave activity and extreme wave conditions in the northern Baltic Sea, *Geophysical Research Abstracts*, **10**, Paper 04128, 2008 (Proc. European Geosciences Union (EGU) General Assembly, Vienna, 13–18 April 2008), CD, 4 lk.

8. Kaitstud lõputööd ja väitekirjad

Magistritöö "Currents dynamics in the Baltic sea, near Lithuanian coast" (2005).
Bakalaureusetöö "Transport waves in semiconductors" (2003).

9. Teadustöö põhisuunad

Waves and coastal processes for engineering applications, nonlinear interaction and mathematical simulation.

10. Tunnustused

Marie Curie stipendiaat (SEAMOCS, TTÜ Küberneetika Instituut, 2007–2009);
Programmi Socrates/Erasmus stipendiaat, 2002.

Paper I

Valdmann, A., Käärd, A., **Kelpšaitė, L.,** Kurennoy, D., Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. *Baltica*, **21**(1-2), 3–12.

Paper II

Kelpšaitė, L., Herrmann, H., Soomere, T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proceedings of the Estonian Academy of Sciences*, **57**(4), 225–231.

Paper III

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

Paper IV

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

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *CIVIL ENGINEERING*

1. **Heino Mölder**. Cycle of investigations to improve the efficiency and reliability of activated sludge process in sewage treatment plants. 1992.

2. **Stellian Grabko**. Structure and properties of oil-shale Portland cement concrete. 1993.

3. **Kent Arvidsson**. Analysis of interacting systems of shear walls, coupled shear walls and frames in multi-storey buildings. 1996.

4. **Andrus Aavik**. Methodical basis for the evaluation of pavement structural strength in Estonian Pavement Management System (EPMS). 2003.

5. **Priit Vilba**. Unstiffened welded thin-walled metal girder under uniform loading. 2003.

6. **Irene Lill.** Evaluation of Labour Management Strategies in Construction. 2004.

7. **Juhan Idnurm**. Discrete analysis of cable-supported bridges. 2004.

8. **Arvo Iital**. Monitoring of Surface Water Quality in Small Agricultural Watersheds. Methodology and optimization of monitoring network. 2005.

9. **Liis Sipelgas**. Application of satellite data for monitoring the marine environment. 2006.

10. **Ott Koppel**. Infrastruktuuri arvestus vertikaalselt integreeritud raudtee-ettevõtja korral: hinnakujunduse aspekt (Eesti peamise raudtee-ettevõtja näitel). 2006.

11. **Targo Kalamees**. Hygrothermal criteria for design and simulation of buildings. 2006.

12. **Raido Puust**. Probabilistic leak detection in pipe networks using the SCEM-UA algorithm. 2007.

13. **Sergei Zub**. Combined treatment of sulfate-rich molasses wastewater from yeast industry. Technology optimization. 2007.

14. **Alvina Reihan**. Analysis of long-term river runoff trends and climate change impact on water resources in Estonia. 2008.

15. **Ain Valdmann**. On the coastal zone management of the city of Tallinn under natural and anthropogenic pressure. 2008.

16. **Ira Didenkulova**. Long wave dynamics in the coastal zone. 2008.

17. **Alvar Toode**. DHW consumption, consumption profiles and their influence on dimensioning of a district heating network. 2008.

18. **Annely Kuu**. Biological diversity of agricultural soils in Estonia. 2008.

19. **Andres Tolli**. Hiina konteinerveod läbi Eesti Venemaale ja Hiinasse tagasisaadetavate tühjade konteinerite arvu vähendamise võimalused. 2008.

20. **Heiki Onton**. Investigation of the causes of deterioration of old reinforced concrete constructions and possibilities of their restoration. 2008.

21. **Harri Moora**. Life cycle assessment as a decision support tool for system optimisation – the case of waste management in Estonia. 2009.

22. **Andres Kask**. Lithohydrodynamic processes in the Tallinn Bay area. 2009.