BOREAL ENVIRONMENT RESEARCH 10: 103–118 ISSN 1239-6095
Helsinki 25 April 2005

Wind wave statistics in Tallinn Bay

Tarmo Soomere

Marine Systems Institute at Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia (e-mail: tarmo@phys.sea.ee); permanent address: Institute of Cybernetics, Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia

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

The wind wave regime of Tallinn Bay, Gulf of Finland, is analysed with the use of a simplified method of long-term computations of wave fields based on a high-resolution nested WAM model and Kalbådagrund (1991–2000) wind data. The distributions of probabilities for wave heights, annual and seasonal mean wave heights, density of wave energy and its flux (wave power), and 1-year return wave heights as well as the wave field properties in extreme storms are computed. The mainland and surrounding islands together with numerous shallow areas shelter the bay from waves coming from the dominating strong wind directions. The average wave properties exhibit a significant seasonal and spatial variability. The highest waves occur in the vicinity of the Tallinn–Helsinki ship lane where the significant wave height exceeds 2 m each year and may reach 4 m in extreme NNW storms.

Introduction

An accurate picture of typical and extreme wave properties is necessary for a wide variety of research topics and engineering applications. Basically, two approaches may be used for obtaining estimates of local wave climate. Wave statistics may be extracted either from long-term wave measurements or from numerically modelled wave fields. Nowadays the second method is about to prevail not only because of the high cost and difficulty of field experiments. Sparse measurements of wave heights at several sites frequently do not contain sufficient information about the wave regime. Another key argument is the rapid increase of the accuracy of wave modelling. The third generation wave models (e.g. Komen *et al*. 1994) adequately represent the sea state even in such a challenging place for wave modellers as the northern Baltic Sea (e.g. Tuomi *et al*. 1999).

Many Baltic Sea countries have performed extensive wave studies in the past and have implemented operational wave models nowadays. Nevertheless, there are only a few surveys of wave climate in the Baltic Sea available in international journals. During the last decade, a few numerical studies of the wave properties have been performed for the southern part of the Baltic Sea (e.g. Gayer *et al*. 1995, Paplińska 2000, Blomgren *et al*. 2001) or for limited areas of the northern Baltic Proper (Soomere 2001a, 2003a). The sources of climatological information, as a rule, do not contain wave information (e.g. Mietus 1998). Older publications (such as Gloukhovsky 1966, Rzheplinsky and Brekhovskikh 1967) are of more historical interest in the present day. The books published in the former Soviet Union (e.g. Davidan *et al*. 1974, 1985, Davidan and Lopatoukhin 1982, Aleshkov 1996) contained valuable measured wave data but were available only in the Russian language.

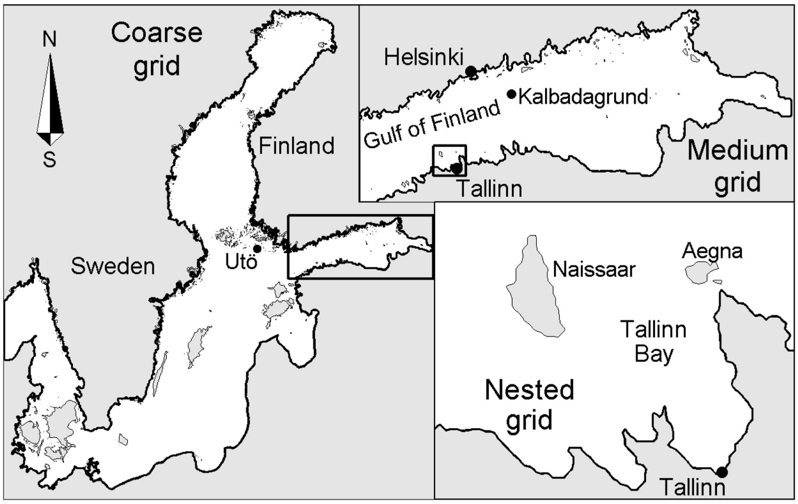

Fig. 1. The coarse, medium and nested wave model grids.

Particularly helpful wave data in sea areas surrounding Finland (including directional wave data from the Bothian Sea and the Gulf of Finland over several years) have been distributed in the form of internal reports (Kahma *et al.* 1983, Kahma and Pettersson 1993, Pettersson 1994) or made available in local report series (Pettersson 2001, Kahma *et al.* 2003). Several studies have been concentrated on specific problems of wave fields (Kahma 1981, Mårtensson and Bergdahl 1987, WASA Group 1995, Mietus and von Storch 1997, Boukhanovsky *et al.* 1999, Pettersson 2004, among others).

Recently, wave statistics for the Baltic Proper have been estimated (Jönsson *et al.* 2002) with the use of the second-generation spectral wave model HYPAS forced by reanalysed HIRLAM wind fields for the year 1999. Another set of experiments was performed with the use of spatially homogeneous winds from different directions. The spatial resolution of the wave model was 11 km. Such a resolution is adequate for the Baltic Proper but insufficient for smaller basins such as the Gulf of Finland where the grid size should not exceed 5 km in order to properly represent the main properties of the local wave field (Pettersson 2004). Further progress in predicting wave statistics can be obtained if one takes into account the likelihood of the winds blowing from those directions and at what strength or how long they are likely to blow (Soomere 2003a).

One of the largest customers of wave forecast and hindcast is marine transport. Detailed wave information is needed, e.g., for route planning and navigation safety purposes. Recently, an acute call for reliable wave statistics arose in connection with the rapid development of fast ferry traffic. The contribution of waves generated by contemporary ships to the entire wave field is significant in regions with relatively low natural wave intensity (PIANC Working Group 41 2003, Soomere *et al.* 2003). Extremely strongly-powered ships may excite waves with considerable energy and with specific properties that are uncommon in natural conditions in sheltered sea areas (Soomere and Rannat 2003). This outcome is especially important in the Baltic Sea conditions, because its brackish water ecosystem is particularly vulnerable with respect to major changes in forcing conditions.

Tallinn Bay (Fig. 1) is an example of a region where a growing concern exists in the local community because of an apparent intensification of the beach processes. It is a relatively well-sheltered sea area with dimensions of about 10 × 20 km in the central part of the Gulf of Finland. For details concerning the Gulf of Finland, the second largest semi-enclosed sub-basin of the Baltic Sea, *see* Alenius *et al.* (1998). The shoreline has been reduced by up to 3 m in some parts of the bay during the last years (Orviku 2001, Kask *et al.* 2003). Significant beach destruction caused by an extreme storm in November 2001 suggests that wind waves mainly govern the beach processes (Kask *et al.* 2003). The increasing intensity and frequency of storms in this area (Alexandersson *et al.* 1998) may partially explain the rapid shoreline reduction.

There is still some evidence that heavy fast ferry traffic plays a perceptible role in the overall intensification of beach processes in Tallinn Bay (Soomere and Kask 2003). Up to 70 daily crossings of the bay by high-speed ships take place in the high season. The bulk power of ship-generated waves forms an appreciable part of the total wave power (Soomere *et al.* 2003). In order to properly quantify the role of anthropogenic waves, it is important to describe the existing wave activity that is formed under influence of several specific features. Sea winds frequently blow along the axis of the Gulf of Finland (Launiainen and Saarinen 1982, Launiainen and Laurila 1984, Keevallik 2003a, 2003b, Soomere and Keevallik 2003). A pronounced peculiarity of waves in elongated basins is that they tend to propagate along the channel axis (Pettersson 2004). The joint influence of these features may result in a particularly mild wave regime in bays such as Tallinn Bay that are well sheltered from waves propagating along the axis of the Gulf of Finland.

The purpose of the current paper is to establish the main properties of the natural wave regime in different parts of Tallinn Bay. I start from an overview of historical wave data in this area. A simplified scheme of the long-term wave hindcast is introduced and its verification against measurements is described. The basic idea consists in reducing long-term calculations to an analysis of a cluster of wave fields precomputed with the use of a triple nested wave model WAM. This technique is justified provided wave fields rapidly become saturated and have a relatively short memory of wind history in the area of interest, and that remote wind conditions insignificantly contribute to the local wave field (Soomere 2003b). As in Jönsson *et al.* (2002), the ice cover during a part of the relatively stormy season is ignored. Wave climate is described in terms of mean and annual maximum wave heights, wave energy and wave power. Their spatial distributions, probabilities for wave heights in selected points and wave fields in extreme storms are analysed.

The historical wave and wind data

The tradition of weather and wave observations in Tallinn harbour (Fig. 2) extends back to 1805 (R. Vahter pers. comm.). The time series have many gaps during 1805–1893 and no records are available from 1921–1946. The older part of the data contains only visual estimates until perspectometers were implemented in 1955 (Orlenko 1984). Unfortunately, the data has not been digitised. A number of wave observations took place during the summer seasons 1973–1980 prior to the 1980 Olympic sailing competitions. A detailed analysis of the data from the 1970s is presented in Orlenko (1984) in terms of the average height $H_{3\%}$ of 3% of the highest waves. Below we shall mostly use the significant wave height H_s defined as the average height of one third of the highest waves. It well coincides with the visually estimated wave height and thus is a proper measure in comparisons of historical data with the results of contemporary wave measurements and modelling. These quantities are related as $H_{3\%} \approx 1.6H_s$ provided the distribution of the wave heights is the Rayleigh distribution (e.g. Massel 1989). The significant period of a wave field is defined as the average period of one third of the highest waves. However, below we mostly use the peak period or the period of the wave component with the largest amplitude.

According to Orlenko (1984), visual observations performed at the breakwaters of Tallinn harbour represent adequately wave properties in the proximity of the harbour but fail to describe the wave regime of the other parts of the bay. For example, the fraction of mixed seas (i.e., wave fields containing both locally generated waves, or windseas, and swell) in the summer season of 1978 is only 2% in the vicinity of the harbour. Ship-based measurements reveal that windseas and mixed seas occur with a roughly equal probability (45%) and swell dominates in about 10% of the cases at the Paljassaare–Miiduranna line (Fig. 2). A possible reason for such a discrepancy is that swell enters Tallinn Bay mostly from the west and is frequently distinguishable in the wave field between the western entrance of the bay and Miiduranna but only seldom reaches the Tallinn harbour area.

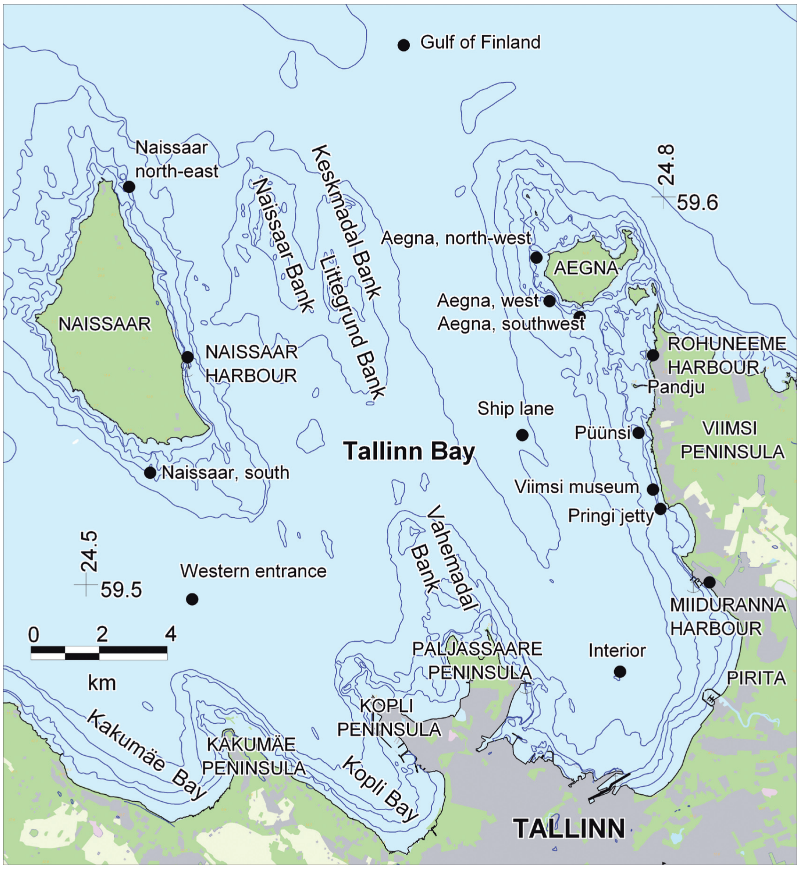

Fig. 2. Map of Tallinn Bay area. Bullets show measurement and reference sites in Table 1. Shown are depth isobaths at 2, 5, 10, 20 and 50 m.

According to the analysis in Orlenko (1984), the wave regime in Tallinn Bay is relatively mild during the summer season. The significant wave height was found not to exceed 0.3 m with a probability of about 50%. Waves with heights < 0.5 m mostly have periods shorter than 2 s. The probability of the wave height exceeding 1.6 m is only 0.3%. The highest waves enter the bay from the west (H_s up to 2 m) or north-west (H_s up to 1 m). The peak period was found not to exceed 3 s with a probability of about 60%. Larger wave heights correspond to longer periods but still the peak periods in the Tallinn Bay area are remarkably short; for example, waves with heights ~1 m have periods 2–3 s. Peak periods > 7 s correspond to swell-dominated seas and occur with the probability of 0.3%. Long waves with heights > 1 m and with periods of 5–6 s are extremely seldom, and occur with a probability of < 0.1%.

Numerical wave modelling can only be useful if based on reliable marine wind information. Frequently, wind properties derived from the atmospheric models are more reliable for the wave hindcast than the measured data (Komen *et al*. 1994, among others). This is not necessarily true in the Baltic Sea conditions (Ennet 1998, Ansper and Fortelius 2003). Its large and complex-shaped water body greatly influences surface-level winds and results in a high variability of the local climate in its vicinity (Mietus 1998, Niros *et al*. 2002). The wind regime in the northern Baltic Proper is strongly anisotropic. The direction of the most frequent and the strongest winds roughly coincides with its axis but is drastically separated from the prevailing direction of geostrophic winds (e.g. Troen and Petersen 1989, Soomere and Keevallik 2001). The sub-basins of the Baltic Sea may have very specific wind climate (Launiainen and Saarinen 1982, Launiainen and Laurila 1984, Soomere and Keevallik 2003).

Since the width of the western part of the Gulf of Finland (about 50–80 km) is comparable with the spatial resolution of the local atmospheric models (typically about 20 km), they at times give inadequate results for this small water body (Ansper and Fortelius 2003). Therefore, measurements of the surface-level wind are used below. The only wind measurement site in the gulf that is not affected by the shore is Kalbådagrund, a caisson lighthouse in the central part of the Gulf of Finland (59°59´N, 25°36´E; Fig. 1). The contrast between wind regimes in different parts of the gulf is significant (Soomere and Keevallik 2003). Its western part is strongly influenced by winds of the Baltic Proper, whereas its eastern part is entirely surrounded by the mainland. Tallinn Bay is well sheltered from the eastern direction but its wave regime may by influenced by winds of the western part of the gulf. For that reason, additionally wind data from Utö (located in the northern Baltic Proper; *see* Fig. 1) are used below.

A simplified method for long-term calculations of the wave regime

The instantaneous wave fields were calculated with the third-generation spectral wave model WAM (Komen *et al*. 1994). This model systematically includes the main effects affecting the wave generation and dissipation as well as non-linear interactions between the wave harmonics. Its current version (cycle 4) takes into account the coastal line of the basin, topographic refraction, spatial and temporal variation of wind properties, wave propagation on the sea surface, quadruplet interactions between wave harmonics, whitecapping, shoaling and wave dissipation in shallow areas due to bottom friction, and interaction of waves and stationary currents. The application of the model for the Baltic Sea is discussed by Soomere (2001a, 2003a).

A triply nested model was used (Fig. 1). A coarse model was run for the whole Baltic Sea on a regular grid with a step of 3´ along latitudes and 6´ along longitudes (step about 3 nm, 208 × 239 grid points, 11545 sea points). In each sea point, 600 spectrum components (24 evenly spaced directions and 25 frequencies ranging from 0.042 to 0.41 Hz with an increment of 1.1) were calculated. In calculations with the wind speed of 6 m s^{-1} an extended frequency range of 42 frequencies (0.042–2.08 Hz) was used in order to correctly represent wave growth in low wind conditions after calm situations (cf. Hasselmann *et al*. 1998). A medium-resolution model was run for the Gulf of Finland with a grid step of 1´ along latitudes and 2´ along longitudes (step about 1 nm, 211 × 91 grid points, 8496 sea points). The bathymetry of the models is based on data from Seifert *et al*. (1995) with a resolution 1´ along latitudes and 2´ along longitudes. A high-resolution model capable of describing the impact of major local topographic and bathymetric features was run for Tallinn Bay and its neighbourhood. Wave data at the open boundaries of the medium and the high-resolution models were taken from the coarse and the medium model, respectively. The grid step of the nested model is 1/4´ along latitudes and 1/2´ along longitudes (step about 1/4 nm, 97 × 69 grid points, 4569 sea points). Its bathymetry is constructed based on maps issued by the Estonian Maritime Board. Such a high-resolution model adequately describes wave refraction at relatively small shallow areas such as Vahemadal Bank, Keskmadal Bank and Littegrund Bank (Fig. 2).

The WAM model is constructed for open ocean conditions where relatively sparse spatial grid and large time step can be used for an adequate representation of the wave field (Komen *et al*. 1994). However, it gives good results in the Baltic Proper (except in a few cases of short severe storms; *see* e.g., Tuomi *et al*. 1999) provided the wind information is correct. It has been frequently speculated that phase-averaged spectral wave models cannot be used in coastal applications where the required spatial resolution is often of the order of 100 m, because the underlying physical assumptions are not necessarily satisfied. The experience of many coastal and shallow water wave models following the principles of the WAM model (TOMAWAC, WAVEWATCH, SWAN, *see* Cavaleri and Holthuijsen 1999, Booij *et al*. 1999, and bibliography therein) demonstrates that their high-resolution versions perform well provided they are numerically stable. The analysis below reveals that basic features of wave fields predicted by the nested model were reliable until a depth of about 5 m and as close to the coast as 200–300 m (*see* also Soomere and Rannat 2003).

Direct long-term high-resolution calculations with the use of contemporary wave models and realistic wind fields are costly and time-consuming. For certain areas and purposes, the expenses can be reduced by introducing specific assumptions. Doing so is generally not acceptable for operational wave forecast systems. However, it is frequently justified in studies of wave climate where the exact knowledge of the sea state at a certain time instant is not critical. The computation scheme used in the current study is based on two assumptions that greatly simplify wave calculations in Tallinn Bay. Firstly, it is assumed that the wave climate in the bay is mostly defined by wind conditions in the proximity of this bay, equivalently, that wind conditions over the whole Baltic Sea may be assumed as spatially homogeneous. The most important implication is that wind properties measured at a single point can be used in wave calculations, equivalently, that wave fields generated in remote areas and possibly by other wind conditions insignificantly contribute to the local wave field. Secondly, it is assumed that the instantaneous local wave field generally does not depend on the waves that existed in this area at the previous time instant of standard meteorological observations except for long-lasting steady wind conditions. These assumptions, if applicable, make it possible to split the long-term calculations into a number of independent sections corresponding to steady and homogeneous wind conditions in the whole Baltic Sea basin.

The assumption of spatially homogeneous wind is apparently justified for the small domain (about 30 × 40 km) of the high-resolution model. Variations of wind conditions eastwards from this domain are generally negligible, because Tallinn Bay is nearly perfectly sheltered from the eastern direction and waves arriving from that direction may only contribute to the wave field in the northernmost part of this bay. Although moderate and strong winds capable of creating substantive wave heights frequently are highly homogeneous in large areas of the Baltic Sea (Soomere 2001b), this assumption generally is not justified in wave calculations in most of the Baltic Proper. However, the geometry of Tallinn Bay and the Gulf of Finland (Fig. 1) is such that waves generated in remote areas may enter Tallinn Bay only from a very narrow direction range (W–WNW). The largest error resulting from the assumption of spatially homogeneous wind occurs if strong wind exists only in the northern Baltic Proper or only in the Gulf of Finland. Such situations apparently occur not often, because strong winds generally cover large sea areas. If a storm covers only the Gulf of Finland, the wave heights and periods are somewhat overpredicted by such a model. If a western storm only blows in the northern Baltic Proper, it results in swell-dominated seas in Tallinn Bay that such a model cannot represent. However, such a storm has a very limited fetch and the resulting swell apparently has a modest height. This feature apparently is one of the main reasons for the particularly small portion of swell-dominated seas (10%) in Tallinn Bay (Orlenko 1984).

The assumption of weak dependence of instantaneous wave fields on the wind history is inspired by the large time step (3 hours) of standard meteorological observations and historical wind data. These data are usually interpreted as mean wind conditions during ±1.5 hours from the measurement instant. This practise is common in many wave studies; for example, the wind data used in Jönsson *et al.* (2002) were analysed every third hour. The large step of wind data suggests that wave fields in small semi-enclosed areas may be practically independent of wave situation at the preceding wind measurement instant for many wind conditions. This property first becomes evident in turning wind conditions. Wave components generated by a wind from a previous direction simply reach the coast or propagate out of the area of interest. Their presence during a part of the time interval between subsequent wind measurements only weakly modifies the new wave field through wave–wave interactions (Komen *et al.* 1994).

The small size of Tallinn Bay and the shape of the Gulf of Finland suggest that the duration of memory of wave fields in this bay frequently is quite short. Waves of practical interest have a period of 2–3 s and generally cross Tallinn Bay (about 10 × 20 km) within one or two hours. Consequently, for an offshore wind from ESE–SW directions, the instantaneous wave field in

Tallinn Bay is independent of waves that filled the bay 3 hours before. The width of the Gulf of Finland is about 50–80 km in the vicinity of Tallinn Bay. Thus, waves generated by northwest, north or northeast winds normally persist in the Tallinn Bay area no longer than 3–4 hours after the wind has changed. The contribution of east winds into the wave field of the bay may last longer. It may cause swell-dominated or mixed seas, or become evident as an additional spectral peak for long waves (cf. Pettersson 2004) in the northernmost part of the bay. The most critical direction is the western one, because waves generated by strong western winds may penetrate into Tallinn Bay through the strait between Naissaar and the mainland (Fig. 2). The modest portion of swell-dominated seas (10%) and the fact that long waves appear very seldom in Tallinn Bay (*see* above) suggest that the assumption of independence of an instantaneous wave field of previous wave fields in turning wind conditions still is an acceptable approximation. However, this approximation apparently is very location-dependent, because the contribution of remote wave conditions to the local wave field increases from the bayhead towards the entrances of the bay and cannot be considered as small in the open part of the Gulf of Finland (Kahma and Pettersson 1993, Pettersson 2001).

If a steady wind blows during a longer time interval, the wave field typically becomes saturated within 6–8 hours in the Baltic Proper (Soomere 2001a; here saturation means that the significant wave height remains constant or increases slowly, by a few cm hour^{-1}, whereas further changes may occur in the wave spectrum). The saturation time may be somewhat longer in the Gulf of Finland where additional time may be needed to build up the wave system propagating along the axis of the gulf in slanted fetch conditions (Pettersson 2004). However, saturation should occur within 10–11 hours and in the current study, the wind history during maximally 12 hours is taken into account. Larger saturation times are reported in Jönsson *et al.* (2002) for violent but unrealistic steady storms with the mean wind speed > 20 m s^{-1} during 24 hours in the whole Baltic Sea.

Wave fields were first computed for steady winds blowing 3–12 hours from 24 evenly spaced directions and having speeds 6 m s^{-1} (for this wind speed an extended frequency range was used), 10 m s^{-1}, 15 m s^{-1} and 20 m s^{-1}. For some directions, wave fields were computed for the wind speed of 23 m s^{-1}. Larger wind speeds are extremely seldom in the Gulf of Finland (Soomere and Keevallik 2003). The coarse model was run only for the western winds. The total number of computed wave tables was about 100. Each table contained main properties of wave fields (wave height, peak and mean period, direction, etc.) at the grid points corresponding to steady wind conditions over the whole Baltic Sea at 1 hour intervals starting from a calm situation. From these tables, only information at each 3rd hour was used in the calculations. An example of the modelled wave field in Tallinn Bay occurring during an extreme NNW storm is shown in Fig. 3.

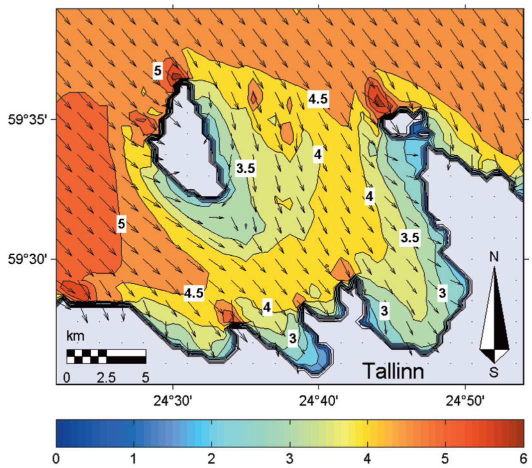

Fig. 3. Modelled significant wave height (m) and wave propagation direction (arrows; one arrow for a cluster of 9 grid points) in Tallinn Bay during an extreme NNW storm when wind 23 m s^{-1} from the direction 330° blows for 6 hours. The wind data roughly correspond to the storm on 15 November 2001. The area represented in the figure contains 65 grid points in the horizontal direction and 55 points in the vertical direction from the high-resolution wave model. Contour interval is 0.5 m.

To the first approximation, it is assumed that an instant wave field in Tallinn Bay is a function of the instantaneous wind speed and direction, and their persistence. The procedure of long-term wave computations was reduced to extracting the proper map of the local wave field from the precomputed maps based on an analysis of the wind history during the last 12 hours as follows:

1. If the wind direction changes more than 22.5° (one angular bin of the wind measurements with a resolution of 16 directions) or if the wind speed increases more than 2 m s^{-1} (in fact ≥ 3 m s^{-1}, because the resolution of the historical wind data is 1 m s^{-1}) between two subsequent measurement instants, the wave field properties were taken equal to those of the sea state excited from calm conditions by a steady wind measured at the later instant and blowing 3 hours.
2. Small changes of the wind direction (< 15–20°) and/or a minor increase of the wind speed that typically lead to rapid adjustment of the wave field (Titov 1969, Komen *et al.* 1994) were treated as steady wind cases corresponding to the wind conditions at the later measurement instant. A decrease of the wind speed generally is also accompanied with a rapid adjustment of wave fields (Titov 1969, Komen *et al.* 1994) and, as different from earlier simulations (Soomere 2003b), it was treated as steady wind as well.
3. If the wind was steady during two, three or four subsequent measurement instants (i.e., within 3, 6 or 9 hours), the properties of the sea state generated from the calm state by such a wind blowing during 6, 9 or 12 hours, respectively, were used.
4. The wave height was set to zero for wind speeds $u \leq 1$ m s^{-1} according to Kahma and Donelan (1988).
5. For wind speeds not equal to 6, 10, 15, 20 or 23 m s^{-1}, a linear interpolation between the relevant maps of wave fields was used to estimate the sea state properties.

Additionally to imperfections of the scheme connected with the assumptions of short memory of wave fields and the adequacy of the one-point wind in the area in question, the model fails to correctly describe the properties of sea state in cases when the wave field essentially depends on the full wind history. A typical situation of this kind occurs when a west or east storm abruptly becomes much stronger without changing its direction. The scheme adequately treats the cases when the wind speed increases by 1–2 m s^{-1}. If, however, the wind speed increases more abruptly, the former wave field essentially affects the latter one but the proposed scheme estimates the sea state at the latter instant based on the latter wind conditions that blow during a certain time over an initially calm situation. As a result, drastic underprediction of the dominating wave periods occurs for a certain time interval (because of an incorrect estimate of the duration of the wind) that may be even accompanied by a certain decrease of the wave height instead of its major increase.

For Kalbådagrund data 1981–2002 (about 60 000 recordings) an already strong (≥ 10 m s^{-1}) WSW–WNW (ESE–NE) wind abruptly increased (at least by 3 m s^{-1} within 3 hours) in about 200 (100) cases. Therefore, this deficiency leads to incorrect results in about 0.5% of the cases. Such events may influence the statistics of very rough seas but owing to their limited number they apparently do not alter much the statistics of typical sea states.

Most of the recent campaigns of wave measurements in Tallinn Bay were carried out during calm days and concentrated on tracking ship-generated waves (Soomere and Rannat 2003). However, a few available data in stronger wind conditions suggest that the described model reasonably reproduces the wave field provided it is forced by high-quality marine wind data. The only station in the Gulf of Finland that is not affected by the shore is Kalbådagrund (Fig. 1) where wind measurements are performed at the height of 32 m above the mean sea level. The suitable height correction factors to reduce the recorded wind speed to the reference height of 10 m are 0.91 for neutral, 0.94 for unstable and 0.71 for stable stratifications (Launiainen and Laurila 1984). To the first approximation, the factor 0.85 was used in the computations. The results show slightly more severe wave climate (in particular, somewhat higher annual maxima of wave heights) than earlier results (Soomere 2003a) based on wind statistics from Helsinki-Isosaari measurement site. This is an expected difference, because Isosaari data only partially represent marine wind conditions (Soomere and Keevallik 2003).

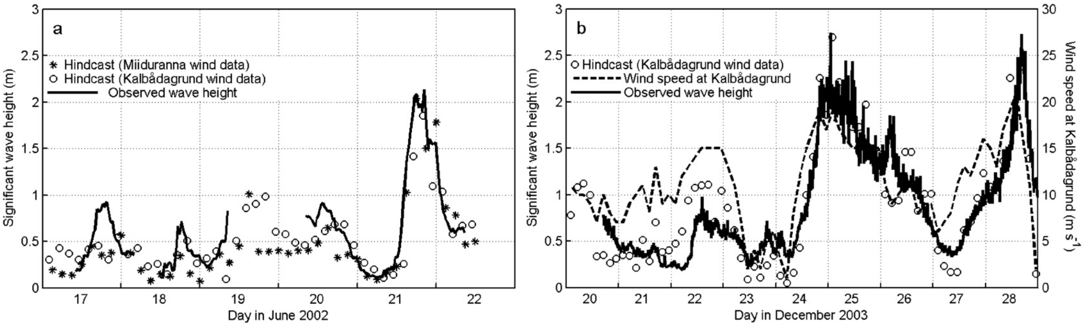

Fig. 4. Measured and modelled significant wave height (**a**) near the western coast of the island of Aegna 17–22 June 2002, (**b**) near the southern coast of the island of Naissaar 20–28 December 2003

The model reasonably represents the wave height during a gale in the coastal zone of Tallinn Bay at a distance of about 300 m from the shoreline at a depth of about 5 m (59°34.5´N, 24°44.6´E). The wave height is underestimated for a fraction of wind conditions with $u \leq 7$ m s^{-1} and $H_s \leq 0.3 - 0.5$ m (Fig. 4a). This feature apparently represents relatively intense ship wash that corresponds to the daily mean significant wave height of 10–20 cm at this site (Soomere and Rannat 2003). If two or three ships pass simultaneously, the wave height may be 30–40 cm during 20–30 minutes. For larger wind wave heights, the role of ship waves is minor. During a gale on 21–22 June, fast ferry traffic was stopped and the measured wave field contained only wind waves. Notice that local wind data from Miiduranna harbour seem to better represent the sea state during this gale and suggest that wind conditions were not homogeneous over a large sea area.

Another series of wave measurements was performed about 600 m from the southern coast of Naissaar (59°31.7´N, 24°31.7´E) in December 2003, at a depth of about 12 m. The model again well captures the temporal behaviour of the significant wave height. Somewhat surprisingly, it correctly reproduces the maxima of wave heights in strong wind conditions (Fig. 4b) provided it was forced by non-corrected wind data. A probable reason for such behaviour is that this site is relatively strongly influenced by waves generated in the northern Baltic Proper in strong west wind conditions. For this wave data series and non-corrected wind data, the bias of the model was about 3 cm and the rms error was about 38 cm.

Distributions of computed wave parameters

The results of computations with the use of the Kalbådagrund data for the years 1991–2000 are expected to adequately describe the wave statistics in Tallinn Bay. Since wind speed decreases towards the eastern part of the Gulf of Finland (Mietus 1998, Soomere and Keevallik 2003), this data may fail to correctly represent wind conditions for certain directions at the western part of this gulf. The contribution of waves excited by western storms to the wave climate of Tallinn Bay can be estimated, to the first approximation, from parameters of wave climate based on a shorter model run (for the year 2000) forced by wind data from Utö (Fig. 1).

The significant wave height is not found to exceed 0.25 m in the south-eastern part of Tallinn Bay and 0.3–0.4 m in its central part with the probability of 50% according to Kalbådagrund wind data (Fig. 5). The wave height does not exceed 0.5–0.75 m between Naissaar and the Viimsi Peninsula and is < 0.5 m south-eastwards the Paljassaare–Aegna line with the probability of 90%. In the central area of the bay, the wave height is lower than 1.25–1.5 m with the probability of 99%. (Notice that in the adjacent open part of the Gulf of Finland this threshold for waves is about 2–2.5 m.) In other words, only during 70–80 hours annually may the significant wave height exceed 1.5 m in the bay. A selection of parameters of wave conditions over the 1990s in certain points of the bay is given in Fig. 6 and in Table 1. These estimates and the statistics agree well with the observations from an earlier time period.

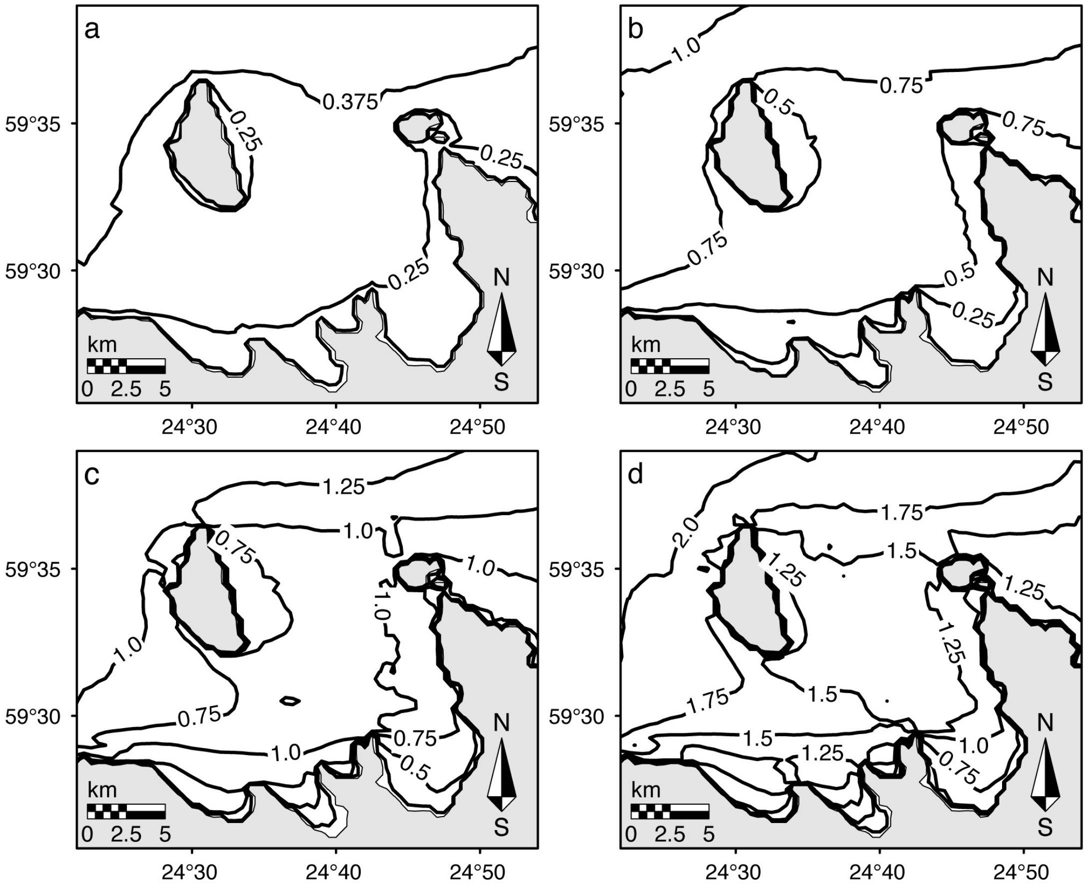

Fig. 5. Distributions of wave heights (m) occurring with the probability of (**a**) 50%, (**b**) 10%, (**c**) 2.5%, and (**d**) 1% according to the method using wind observations from Kalbådagrund (1991–2000).

Table 1. Computed parameters of the wave regime in different areas of Tallinn Bay according to Kalbådagrund wind data (1991–2000). The location of the points is given in Fig. 2. Several sites roughly correspond to the ship wave measurement sites in Soomere and Rannat (2003). A = Annual, S = Summer, W = Winter.

Area	Depth (m)	Maximum wave height (cm)		Mean wave height (cm)			Mean energy density (J m^{-2})			Mean power density (W m^{-1})		
		A	S	A	S	W	A	S	W	A	S	W
Interior of the bay	23	203	122	26	24	28	137	93	181	223	121	325
Pringi jetty	8	231	148	31	26	36	220	143	296	375	205	545
Viimsi museum	8	249	156	33	28	38	244	157	330	425	229	621
Püünsi	5	247	157	33	28	38	238	153	322	434	236	632
Aegna, south-west	7	231	152	35	30	40	247	164	330	423	238	608
Aegna, west	6	270	186	41	35	47	336	224	448	652	389	915
Aegna, north-west	6	279	216	43	37	49	372	266	478	734	483	985
Naissaar, harbour	7	228	193	27	25	29	175	158	191	341	297	385
Ship lane	58	266	170	40	34	46	325	213	436	556	305	807
Western entrance	18	313	215	45	39	51	424	291	556	840	487	1190
Naissaar, north-east	6	302	254	33	30	36	266	229	302	569	470	668
Gulf of Finland	85	358	290	56	48	65	644	460	828	1210	805	1610

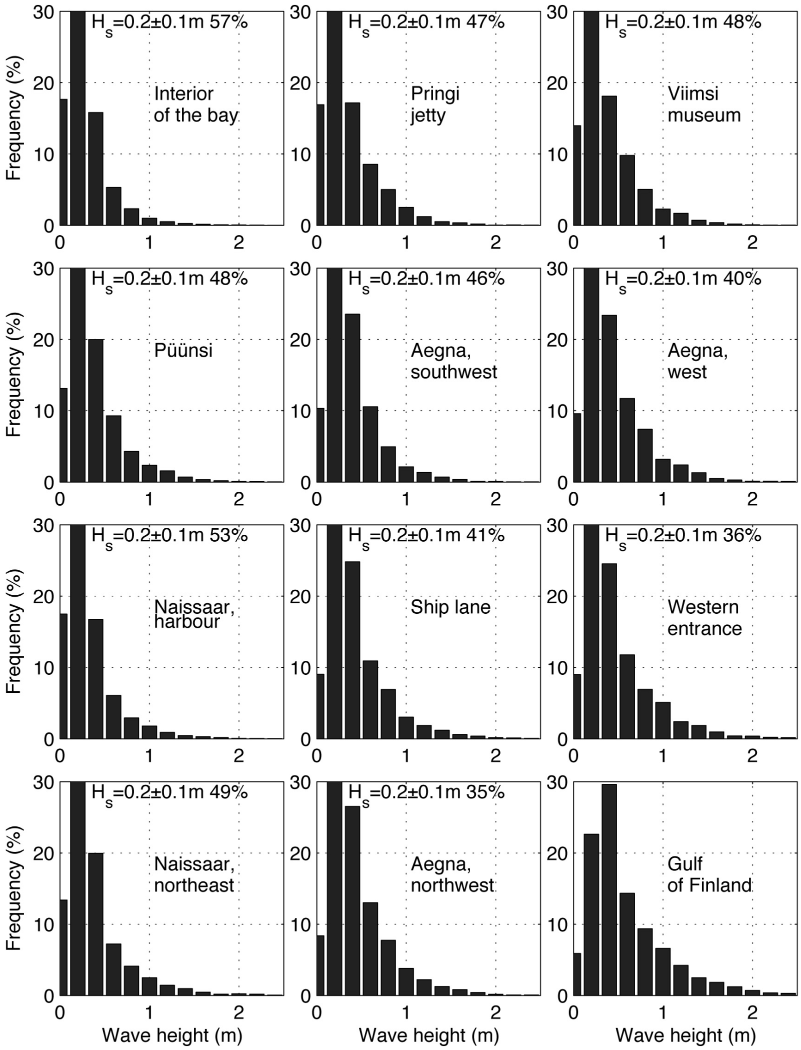

Fig. 6. Frequency of occurrence of waves of different heights in certain locations of Tallinn Bay according to the method using Kalbådagrund (1991–2000) wind data. The reference points are shown in Fig. 2. The leftmost bar in each panel corresponds to calm conditions (H_s < 0.1 m).

Wave heights in the eastern part of the bay are somewhat lower than in the rest of the bay. For example, with the probability of 99% wave heights do not exceed 1 m in the nearshore and 1.25 m at a distance of about 1 km from the shoreline of the Viimsi Peninsula. An analogous area of low waves near Naissaar is quite small and hardly evident in Fig. 5. This is a somewhat surprising feature (because high waves generally are expected to enter the bay during western or north-western winds and to create rough seas in the deep-water area next the Viimsi Peninsula) that apparently results from the specific combination of the dominating winds and the geometry of Tallinn Bay.

An estimate of the 1-year return wave height is calculated as the mean value of annual maxima of the significant wave height at each sea point over the time period 1991–2000. Its distribution (Fig. 7) suggests that the highest waves occur during NW storms and enter the bay through its northern entrance. Their height reaches about 2.5 m each year in the centre of the bay (whereas in the adjacent central area of the Gulf of Finland the typical annual maximum wave height may reach 3.6–4 m). Locally, relatively high waves may occur near the Paljassaare Peninsula and the Kakumäe Cape as well as off the north-western coast of Aegna owing to topographical refraction (cf. Soomere 2001a). An extensive area with rel-

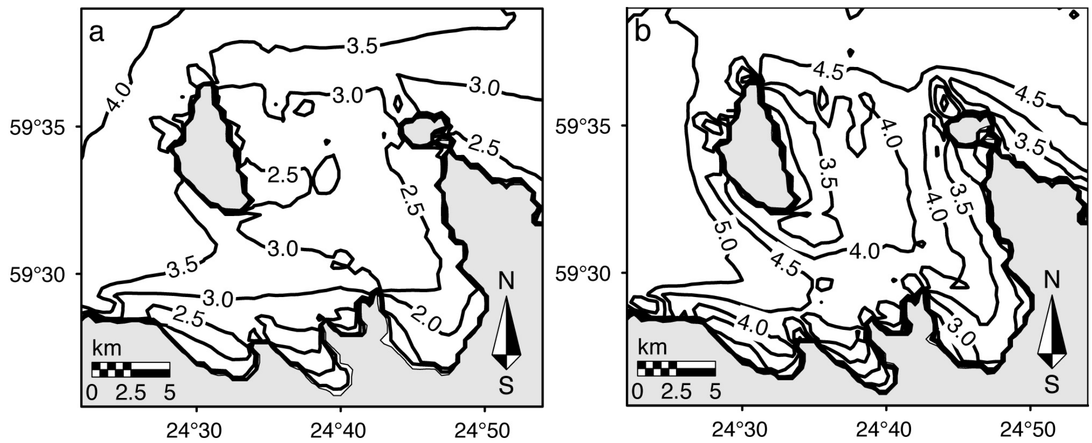

Fig. 7. (**a**) Distribution of the 1-year return wave heights (m) based on Kalbådagrund (1991–2000) wind data; (**b**) same but based on the Utö (2000) data. Contour interval is 0.5 m.

atively low waves is located off the south-eastern coast of Naissaar. Another domain with a low wave intensity (where the 1-year return wave heights are close to 2 m) lies along the western coast of the bay. The vicinity of Tallinn harbour is a particularly mild sea area. This property of the local wave regime has apparently been known for a long time, otherwise Tallinn would have been built in some other place. Notice that wave intensity eastwards of the Viimsi Peninsula is essentially higher than in Tallinn Bay.

The annual maxima of wave heights normally occur in autumn and winter (October–March; Table 1). The wave height in summer (April–September) is found not to exceed 1.6–1.8 m in the northern part of the bay and 1.3–1.5 m in the southern part. The wave periods in summer are shorter than in winter. This property is apparently common for the whole Baltic region (Jönsson *et al.* 2002). The difference in periods may partially come from the seasonal variation of the directional structure of the strongest winds (Mietus 1998, Jönsson *et al.* 2002, Soomere and Keevallik 2003). During the autumn and winter seasons, west and north-west winds dominate among strong winds, thus the fetch of the highest waves is much larger than during the summer months.

The climatological values of the maximum wind speed may reach 35–40 m s^{-1} in the area in question (e.g. Anonymous 1966, Prilipko 1982). These values represent mostly wind speed in short gusts and are of minor importance for wind-wave studies, because the sea state represents the wind conditions in large sea areas during many hours. The 3-hour mean wind speed in extreme storms occurring once a century in the Gulf of Finland is 23–24 m s^{-1} (Soomere and Keevallik 2001, 2003) and roughly corresponds to annual maximum wind speed in the northern Baltic Proper (Soomere 2001b). Therefore, the extreme wave fields from model calculations with the use a typical one-year wind data from the Baltic Proper can be interpreted as an estimate of 100-year return wave conditions in Tallinn Bay. The 1-year return wave heights calculated on the basis of the Utö wind data for the year 2000 are nearly twice as high as the heights based on the Kalbådagrund data (Fig. 6). The maximum wave height is about 4 m in the vicinity of the Tallinn–Helsinki ship lane. In most of the coastal areas of Aegna, Naissaar and the Viimsi Peninsula the centennial wave height does not exceed 2.5–3 m suggesting that the bay is well sheltered from open sea waves. Two areas with relatively small wave intensity (one near the south-eastern part of Naissaar and another between Rohuneeme harbour and Aegna) can be distinguished in Fig. 6.

A most prominent storm took place in November 2001 in the northern Baltic Proper. It was so ferocious that wind sensors at Kalbådagrund did not function properly during part of it. According to the data from the western part of

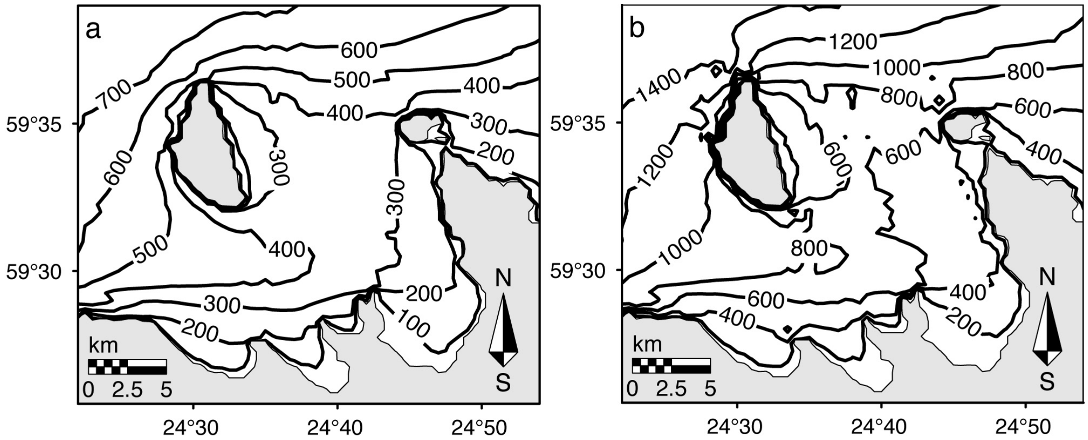

Fig. 8. (**a**) Mean energy density of wind waves (contour interval 100 J m^{-2}) and (**b**) mean wave power (contour interval 200 W m^{-1}) based on Kalbådagrund (1991–2000) wind data is 0.5 m.

the Gulf of Finland (T. Tomson pers. comm.), the maximum 6-hour mean wind speed during this storm was about 23 m s^{-1}. The modelled significant wave heights in this storm mainly coincide with the 100-year return wave heights (compare Fig. 3 with Fig. 7). This suggests that it was a 1 in 100 years event. According to the model, the maximum wave height in the central part of the gulf probably reached 5 m; the observed significant wave height, however, slightly exceeded 5 m for a short time (Pettersson and Boman 2002). The wave height apparently was 4 m and the peak period 6–7 s in the vicinity of the Tallinn–Helsinki ship lane in Tallinn Bay. Topographic refraction caused concentration of a part of energy of such high and long waves in shallow areas northwards from Aegna and Naissaar. The model predicts wave height up to 6 m at the downwind side of shallow areas (cf. Fig. 7). That high waves are improbable owing to eventual wave breaking at small-scale reefs in these areas. As a result, a large portion of the wave energy was redistributed or lost in the vicinity of these areas and did not propagate into the bay. The wave height southwards of the shallow regions was about 20% smaller than in the proximity of the Tallinn–Helsinki ship lane. An analogous phenomenon occurs due to shallow areas between Naissaar and the mainland during strong western storms.

A useful measure of the wave regime is the mean energy density of a wave field per unit of sea area that is proportional to the wave height squared. Another important property is the density of energy flux or power carried by waves per unit of length of the wave crest. It is defined as the product of the energy density and the group speed of a wave, and characterises the energy exchange between different sea domains. To the first approximation, wave power was estimated based on the assumption that the entire energy of a wave field propagates with the group velocity of the wave corresponding to the peak of the energy spectrum.

Decadal mean values of wave energy and power at certain locations of Tallinn Bay are given in Table 1. Their spatial distribution is shown in Fig. 8. Both measures are much smaller in Tallinn Bay than in the open part of the Gulf of Finland. Their spatial distributions are similar to the distributions of wave heights (cf. Fig. 5 and Fig. 7). The maximums of energy density and power occur in the northernmost and in the western parts of the bay. Both have considerable seasonal variation that is the largest (up to 50% from the annual mean) in the inner area of the bay in the vicinity of Tallinn harbour, and relatively modest (about 20%–30%) at the entrances to the bay. These measures also vary to a large extent in different regions of the bay. In particular, in specific coastal areas (the coastal zone from the western part of Aegna down to the southern part of Tallinn Bay and the vicinity of the south-eastern coast of Naissaar) they both have considerably smaller values than in the centre of the bay (Table 1).

Conclusions and discussion

The rapid saturation of wind waves and relatively short memory of the wave field in changing wind conditions allows the use of precomputed wave patterns in estimates of the long-term wave climate in the small and well-sheltered basin of Tallinn Bay. Such a simplified approach well describes wave properties in both rapidly changing and more or less stable wind conditions. It fails in a relatively small number of specific situations. For example, it overestimates heights and periods of waves generated by short storms, underestimates those in short calm intervals between gales, and fails to describe changes in wave fields in storms where wind speed abruptly increases. In particular, predictions of rough sea states in rapidly changing storms may frequently fail owing to these limitations. However, statistics of typical sea states apparently are consistent. Indeed, estimates of statistics of wave fields with the significant wave height > 0.3 m (Fig. 6) well agree with the observations from an earlier period (Orlenko 1984) for the summer season.

Since no results of long-term wave measurements in the open part of the bay are available and a very limited comparison of the modelled and measured data has been made, the estimated parameters of the wave regime should be considered as indicative. The results should be interpreted as estimates of the upper bounds of parameters of the long-term wave climate, because the presence of the ice cover during a notable part of the relatively stormy season is ignored. In particular, the values of annual maxima of wave heights may be overestimated, because a part of strong storms occurs during the winter season when sea ice is present. However, the qualitative features of spatial distributions of the local wave field (incl. comparison between the bay area and the open part of the Gulf of Finland) apparently are reliable.

Although very rough seas may occasionally occur in the central part of Tallinn Bay during extreme storms, generally the wave regime of this region is relatively mild as compared with that in the open part of the Gulf of Finland. The highest waves enter the bay during extreme north-west storms when particularly rough seas may occur in the whole bay. High waves may occur at its western entrance during extreme west storms; however, certain parts of the bay are well sheltered from waves from this direction. The significant wave height in extreme centennial storms from unfavourable directions (in particular, NNW) may reach 4 m in the central area of the bay, and is about 3 m in certain nearshore areas of the western coast of Aegna and the Viimsi Peninsula.

There are several reasons for such low natural wave activity in the bay. First, the islands of Naissaar and Aegna, and the Viimsi Peninsula shelter the bay from waves of certain wind directions. Second, wind regime in this area is strongly anisotropic (Launiainen and Saarinen 1982, Launiainen and Laurila 1984, Soomere and Keevallik 2003). The highest waves in the neighbouring sea areas are mainly generated by the western, north-western or eastern winds (Soomere and Keevallik 2003) but the bay is well sheltered from a part of these winds. Third, numerous banks and shallow areas located at the entrances of the bay (Naissaar Bank, Keskmadal Bank and Littegrund Bank between Aegna and Naissaar, Vahemadal Bank between Naissaar and the Paljassaare Peninsula) shelter the inner parts of the bay. The shallowest parts of the banks directly shelter the downwind regions. Topographical refraction plays an important role at somewhat larger depths. It redirects a part of waves so that less wave energy enters the bay. In some cases, areas of anomalously high wave energy concentration may become evident in the vicinity of the banks. In these cases, a part of wave energy is dissipated owing to more intense wave breaking in such areas. The sheltering role of the shallow areas at the entrances of the bay is particularly well evident in rough seas.

The wave regime of Tallinn Bay exhibits notable temporal variability. It has a significant annual variation, with a relatively stormy autumn and winter period, and calm spring and summer. The average significant wave height during the windy autumn and winter season is about 50% higher than during the rest of the year. The average wave energy and its flux also vary considerably in different seasons. The wave regime has also a strong spatial variability. Several coastal regions are particularly favourably sheltered from high waves. A relatively low average wave energy level apparently is found near the south-eastern part of Naissaar, the south-western coast of Aegna and the western coast of the Viimsi Peninsula. Those areas partially overlap with regions where 1-year and 100-year return wave heights are relatively small. The overlapping domains are located in the southernmost part of the eastern coast of Naissaar, and between Rohuneeme harbour and Aegna. The existence of regions with a particularly mild wave regime apparently results from the interplay of the geometrical features and emplacement of Tallinn Bay with the specific properties of the wind field in the Gulf of Finland.

Acknowledgements: The study was supported by the Estonian Science Foundation (Grant 5762). The author is deeply grateful to the Finnish Meteorological Institute for providing wind data from Utö and Kalbådagrund (Dno 8/410/03), to Dr. Tarmo Kõuts for providing wind data from Miiduranna, to Dr. Teolan Tomson for providing wind data of the November 2001 storms, to Dr. Kimmo Kahma for inspiring discussions, and to anonymous referees for their very helpful comments and suggestions.

References

Alenius P., Myrberg K. & Nekrasov A. 1998. The physical oceanography of the Gulf of Finland: a review. *Boreal Env. Res.* 3: 97–125.

Aleshkov Yu.Z. [Алежков Ю.З.] 1996. [*Oceanic currents and waves*]. Leningrad State University, Leningrad. [In Russian].

Alexandersson H., Schmith T., Iden K. & Tuomenvirta H. 1998. Long-term trend variations of the storm climate over NW Europe. *Global Atmos. Ocean System* 6: 97–20.

Anonymous 1996. [*Handbook of climate of the USSR, vol. 4: Estonian SSR, part 3: Wind*]. Gidrometeoizdat, Leningrad. [In Russian].

Ansper I. & Fortelius C. 2003. HIRLAM-mudeli tuuleprognoosi hindamine Läänemerel. *Publicationes Instituti Geographici Universitas Tartuensis* 93: 195–205.

Blomgren S., Larsson M. & Hanson H. 2001. Numerical modelling of the wave climate in the southern Baltic Sea. *J. Coastal Res.* 17: 342–352.

Booij N., Ris R.C. & Holthuijsen L.H. 1999. A third-generation wave model for coastal regions. 1. Model description and validation. *J. Geophys. Res.* C104: 7649–7666.

Boukhanovsky A.V., Lavrenov I.V., Lopatoukhin L.J., Rozhkov V.A., Divinsky B.V., Kos'yan R.D., Ozhan E. & Abdalla S. 1999. Persistence wave statistics for Black and Baltic seas. In: *Proc. Int. MEDCOAST Conf. "Wind and wave climate of the Mediterranean and the Black Sea"*, Antalya, Turkey, pp. 199–210.

Cavaleri L. & Holthuijsen L.H. 1999. Wave modelling in the WISE group. In: Edge B.L. (ed.), *Coastal engineering 1998. Proceedings of the 26th international conference 22–26 June 1998, Falconer Hotel, Copenhagen, Denmark*, American Society of Civil Engineering (ASCE), vol. 1, pp. 498–508.

Davidan I.N., Lopatoukhin L.I. & Rozhkov V.A. [Давидан И.Н., Лопатухин Л.И. & Рожков В.А.] 1974. [*Wind and waves in the oceans and seas. A reference book*]. Register of shipping USSR. Transport, Leningrad. [In Russian].

Davidan I.N., Lopatoukhin L.I. & Rozhkov V.A. [Давидан И.Н., Лопатухин Л.И. & Рожков В.А.] 1985. [*Wind waves in the world oceans*]. Gidrometeoizdat, Leningrad. [In Russian].

Davidan I.N. & Lopatoukhin L.I. [Давидан И.Н. & Лопатухин Л.И.] 1982. [*A rendezvouz with storms*]. Gidrometeoizdat, Leningrad. [In Russian].

Ennet P. 1998. Wind data as measured and as calculated by HIRLAM. In: Tamsalu R. (ed.), *The coupled 3D hydrodynamic and ecosystem model FINEST*. Report series of the Finnish Institute of Marine Research 35: 47–48.

Gayer G., Günther H. & Winkel N. 1995. Wave climatology and extreme value analysis for the Baltic Sea area off the Warnemünde harbour entrance. *Deutsche Hydrographische Zeitschrift* 47: 109–130.

Gloukhovsky B.H. [Глуховский Б.Х.] 1966. [*Investigations of wind waves*]. Gidrometeoizdat, Leningrad. [In Russian].

Hasselmann S., Bennefeld C., Graber H., Hauser D., Jackson F., Vachon P., Walsh J., Hasselmann K. & Long R.B. 1998. *Intercomparison of two-dimensional wave spectra obtained from microwave instruments, buoys and WAModel simulations during the Surface Wave Dynamics Experiment*. Report No 258. MPI für Meteorologie, Hamburg.

Jönsson A., Broman B. & Rahm L. 2002. Variations in the Baltic Sea wave fields. *Ocean Engineering* 30: 107–126.

Kahma K. 1981. On two-peaked wave spectra. *Finnish Marine Research* 248: 87–116.

Kahma K. & Donelan M. 1988. A laboratory study of the minimum wind speed for wind wave generation. *J. Fluid Mech.* 192: 339–364.

Kahma K. & Pettersson H. 1993. Wave statistics from the Gulf of Finland. *Finnish Institute of Marine Research, Internal report* 1/1993. [In Finnish with English summary].

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

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

Kask J., Talpas A., Kask A. & Schwarzer K. 2003. Geological setting of areas endangered by waves generated by fast ferries in Tallinn Bay. *Proc. Estonian Acad. Sci. Eng.* 9: 157–184.

Keevallik S. 2003a. Tallinna lahe tuuled. *Publicationes Instituti Geographici Universitatis Tartuensis* 93: 217–226.

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

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

Launiainen J. & Laurila T. 1984. Marine wind characteristics in the northern Baltic Sea. *Finnish Mar. Res.* 250: 52–86.

Launiainen J. & Saarinen J. 1982. Examples of comparison of wind and air-sea interaction characteristics on the open sea and in the coastal areas of the Gulf of Finland. *Geophysica* 19: 33–46.

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

Massel S.R. 1989. *Hydrodynamics of coastal zones*, Elsevier, Amsterdam, Oxford, New York, Tokyo.

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

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

Niros A., Vihma T. & Launiainen J. 2002. Marine meteorological conditions and air-sea exchange processes over the northern Baltic Sea in 1990s. *Geophysica* 38: 59–87.

Orlenko L.R. [Орленко Л.Р.] (ed.) 1984. [*Studies of the hydrometeorological regime of Tallinn Bay*]. Gidrometeoizdat, Leningrad. [In Russian].

Orviku K. 2001. Eesti rannad kahanevad. *Maaleht* 24.05.2001.

Paplińska B.E. 2000. Case study of wave dependent drag coefficient in the Baltic Sea. *Meteorologische Zeitschrift* 9: 67–72.

Pettersson H. 1994. Directional wave statistics from the southern Bothnian Sea 1992. *Finnish Institute of Marine Research, Internal report* 5/1994. [In Finnish with English summary].

Pettersson H. 2001. Directional wave statistics from the Gulf of Finland 1990–1994. *MERI — Report Series of the Finnish Institute of Marine Research* 44: 1–37. [In Finnish with English summary].

Pettersson H. 2004. *Wave growth in a narrow bay*, Ph.D. thesis, Finnish Institute of Marine Research, Contributions no. 9.

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

PIANC Working Group 41 2003. *Guidelines for managing wake wash from high-speed vessels*. International Navigation Association (PIANC), Brussels.

Prilipko G.I. (ed.) [Прилипко Г.И.] 1982. [*Climate of Tallinn*]. Gidrometeoizdat, Leningrad. [In Russian].

Rzheplinsky G.V. & Brekhovskikh Yu.P. [Ржеплинский Г.В. & Бреховских Ю.П.] (eds.) 1967. [*Wave atlas for Gulf of Finland*]. Gidrometeoizdat, Leningrad. [In Russian].

Seifert T., Kayser B. & Tauber F. 1995. *Bathymetry data of the Baltic Sea*. Baltic Sea Research Institute, Warnemünde.

Soomere T. 2001a. Wave regimes and anomalies off northwestern Saaremaa Island. *Proc. Estonian Acad. Sci. Eng.* 7: 157–173.

Soomere T. 2001b. Extreme wind speeds and spatially uniform wind events in the Baltic Proper. *Proc. Estonian Acad. Sci. Eng.* 7: 195–211.

Soomere T. 2003a. Anisotropy of wind and wave regimes in the Baltic Proper. *Journal of Sea Research* 49: 305–316.

Soomere T. 2003b. Tallinna lahe loodusliku lainetuse režiimist. *Publicationes Instituti Geographici Universitatis Tartuensis* 93: 227–241.

Soomere T., Elken J., Kask J., Keevallik S., Kõuts T., Metsaveer J. & Peterson P. 2003. Fast ferries as a new key forcing factor in Tallinn Bay, *Proc. Estonian Acad. Sci. Eng.* 9: 220–242.

Soomere T. & Kask J. 2003. A specific impact of waves of fast ferries on sediment transport processes of Tallinn Bay. *Proc. Estonian Acad. Sci. Biol. Ecol.* 52: 319–331.

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

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

Soomere T. & Rannat K. 2003. An experimental study of wind waves and ship wakes in Tallinn Bay. *Proc. Estonian Acad. Sci. Eng.* 9: 157–184.

Titov L.F. [Титов Л.Ф.] 1969. [*Wind waves*]. Gidrometeoizdat, Leningrad. [In Russian].

Troen I. & Petersen E. L. 1989. *European wind atlas*. Risø National Laboratory, Roskilde, Denmark.

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

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

Received 10 November 2003, accepted 10 December 2004