Anisotropy of wind and wave regimes in the Baltic proper

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Abstract

The directional distribution of moderate and strong winds in the Baltic Sea region is shown to be strongly anisotropic. The dominating wind direction is south-west and a secondary peak corresponds to north winds. North-west storms are relatively infrequent and north-east storms are extremely rare. Angular distribution of extreme wind speed also has a two-peaked shape with maxima corresponding to south-west and north winds, and a deep minimum for easterly winds. The primary properties of the anisotropy such as prevailing winds, frequency of their occurrence, directional distribution of mean and maximum wind speeds coincide on both sides of the Baltic proper. The specific wind regime penetrates neither into the mainland nor into the Gulf of Finland or the Gulf of Riga.

Properties of the saturated wave field in the neighbourhood of proposed sites of the Saaremaa (Osel) deep harbour are analysed on the basis of the wave model WAM forced by steady winds. The directional distribution of wave heights in typical and extreme storms is highly anisotropic. Remarkable wave height anomalies may occur in the neighbourhood of the harbour sites.

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1. Introduction

The wind field in the Baltic proper and adjacent regions is traditionally held to be more or less directionally homogeneous (Handbook, 1966; Estonian Climate Atlas, 1969; Prilipko, 1982). Indeed, the area is without large-scale effects causing strong anisotropy, and it is a prolongation of the North Atlantic storm track (Hoskins and Valdes, 1990; Rogers, 1997), where the frequent occurrence of high-latitude cyclones leads to high wind variability. There are two major causes of deviation of the directional wind distribution from the isotropic one. Firstly, a slight prevalence of west winds stems from the large-scale western airflow at these latitudes. Secondly, the interplay of the North Atlantic Low (a large low pressure region near Iceland) and the Siberian High (a high pressure region covering much of the Eurasian continent) explains the prevalence of south-west winds during late autumn and winter. The anisotropy is quite limited and the frequency of winds from different directions varies about 30% (e.g. Bergström, 1992; Kull, 1996; Mohr and Sandström, 1996; Köuts, 1998).

It is known that the directional structure of moderate (6–10 m/s) and strong (>10 m/s) winds is generally strongly anisotropic. Perhaps the clearest evidence of the wind anisotropy in the Baltic proper is
the historically well-established fact that the strongest storms blow from south-west, west or north. Indeed, the angular wind distribution in the stormy seasons contains more south-west winds (in the Baltic proper) or south-east winds (in the Gulf of Riga area) than in calm April–June, when the distribution is more or less isotropic (Bergström, 1992a,b; Handbook, 1966; Köuts, 1998). A highly anisotropic angular distribution of certain wind parameters has recently been established for the Baltic proper (Soomere and Keevallik, 2001). Although the time series used in their analysis (1977–1991) were somewhat shorter than usual in climatological studies, the existence of this specific wind structure in the Baltic Sea area was likely because the distributions of maximum wind speed, frequency of events of moderate and strong winds, and mean wind speed on both sides of the Baltic proper qualitatively coincided.

The acute need for quantifying the wind anisotropy arose in the framework of the hydrodynamical studies of possible deep harbour sites in the north-western part of Saaremaa Island (Elken et al., 2001). Wave regime is a critical parameter in such studies, because the harbour configuration, height of breakwaters and quays will depend on it, as will the required stability of the constructions. The existing wave atlas (Rzhelplinsky and Brekhovskikh, 1967) and visual estimates of wave heights at several sites (Elken et al., 2000) provide insufficient information on wave regime. Generally, wave regime and loads can be satisfactorily estimated only on the basis of reliable wind information.

Re-analysis of data from the coastal areas of Estonia, Sweden and Finland (Section 2) reveals that the wind regime in the Baltic proper is indeed highly anisotropic. Although open sea wind properties may greatly differ from those of the mainland, the analysis confirms that (as suggested in Tomson and Hansen, 2000; Soomere, 2001b; Tomson, 2001) Vilsandi data well represent the wind regime off the coast of Saaremaa.

To forecast extreme waves, it is necessary to correctly estimate the strongest possible winds on the open sea. The most important result of the study was to establish the highly anisotropic directional distribution of extreme wind speed in long-lasting storms off the north-western coast of Saaremaa (Section 3). Based on this information, directional distribution of wave properties during typical and extreme storms in the neighbourhood of three proposed harbour sites is calculated in Section 4. It is also demonstrated that remarkable wave height anomalies may occur in the neighbourhood of the harbour sites.

2. Anisotropy of wind field in the Baltic proper

The analysis below relies on four data sets recorded (1) at Vilsandi, Ristna and Sörve weather stations located on the eastern coast of the Baltic Sea, (2) at Ruhnu (1961–2000), Virtsu and Pärnu (1992–1995) weather stations (Köuts, 1998) in the Gulf of Riga and Moonsund, (3) at five Finnish weather stations on the northern coast of the Baltic proper (1961–2000) and (4) at Näsudden (Gotland, 1980–1989) (Fig. 1).

Wind speed and direction at the Estonian sites were filed as an average of a 10-min period every three hours starting from 0.00 GMT. The angular resolution of filing was 16 directions. The data from the Finnish sites were recorded every three hours with angular...
resolution of $10^\circ$ (36 directions). Wind speed at Näsudden was measured continuously at seven heights (10–145 m). Wind direction was measured with an accuracy of a few degrees at three heights. In the following, hourly averaged wind data at the height of 38 m level are used, because basic scalar properties of the wind at that level well match those of Finnish and Estonian coastal weather stations. Data from Ruhnu, Pärnu and Virtsu as well as from Harilaid Islet (1997–98, Tomson and Hansen, 2000) show that the mean wind speed in Moonsund and the Gulf of Riga is either comparable to (Harilaid, Sõrve) or less than (Virtsu, Pärnu) that in the Baltic proper (Soomere, 2001b). In general, somewhat lower wind speed values were recorded at Ristna than at neighbouring sites. Most probably, a forest nearby reduces the wind speed, in particular from the northerly direction (see below).

The deviations of the traditional wind rose from the isotropic shape are about 30% at all measurement sites. The situation changes drastically if one excludes the “background” of weak winds that constitute 50 to 70% of the total number of recordings. The directional distribution of moderate and strong winds is strongly anisotropic. Typically, it has a two-peaked shape that is most spectacular at Vilsandi. An extremely high peak corresponds to south-west winds and a somewhat lower peak to north winds (Fig. 2a, b). The

![Diagrams](image-url)  
Fig. 2. Directional distribution of all winds (solid line), winds $\geq 6$ m/s (dashed line) and strong winds (>10 m/s, dotted line): (a) at Vilsandi 1977–1991, (b) at Ristna 1977–1991, (c) at Näsudden 1980–1988, at 38 m level, (d) at Ulö 1961–2001. Vertical axis represents relative frequency of occurrence (%) of wind events. Notice that angular resolution is 22.5° (a, b, c) or 10° (d).
prevalence of westerlies apparently results from the overwhelming dominance of west winds in the global circulation. However, the secondary maximum for north winds is rather anti-correlated with the geostrophic wind that generally has a deep minimum for north winds in Sweden and Denmark (Persson and Kindell, 1981; Petersen et al., 1981).

The local minimum for north-west winds is highly interesting, because it is not caused by the large-scale circulation and, for example, the Vilsandi measurement site is open in that direction. Another interesting feature is that the two-peaked distribution exists during all seasons (whereas the location of both peaks is fixed) including the summer months when the global air pressure distribution generally does not support south-west winds. Moreover, south-west winds do not prevail during winter at Vilsandi although they are believed to dominate in the Baltic proper (Soomere and Keevallik, 2001). The rate of anisotropy of moderate and strong winds somewhat depends on the measurement site but generally the frequency of winds from different directions is more than 10 times higher than in historical data (Handbook, 1966; Soomere, 2001b). This can be seen as evidence that the structure of the Baltic Sea wind field has changed during the last decades.

The screening effect of the mainland may damp east winds on the eastern coast of the Baltic Sea. However, data from Ölands södra grund (1961–70, 1982–89) and Almagrundet (1976–1995) show a deep minimum for east winds on the western coast of the Baltic proper, whereas the portion of east and south-east winds is even smaller than on the eastern coast (Bergström, 1992a; Mohr and Sandström, 1996). They also reveal a secondary peak corresponding to north winds during stormy periods. During the relatively calm period, another minor peak for north-east and east winds appears, evidently reflecting the existence of a minor maximum for north-east and east geostrophic winds during April–September (Persson and Kindell, 1981).

At Näsudden, the directional wind pattern is similar to the one described above (Fig. 2c). The traditional wind rose is more anisotropic than at the Estonian sites and has a relatively wide peak for south-west winds. The distribution of moderate and strong winds is strongly anisotropic, and contains two maxima. The main peak corresponds to south-west winds and a minor peak to NNW winds. The relatively low frequency of north winds at Näsudden (as well as a certain shift of the north peak in a westerly direction) apparently results from the screening effect of Gotland. The wind regime at Utö Island (Fig. 2d) is most similar to the one described and contains well-defined peaks for SW and NNW winds.

The basically nontrivial feature of the described distributions is that the peaks are located in the same direction on all coasts of the northern Baltic proper. If the directional anisotropy was caused by the screening effect of the mainland, the minima of the distributions would correspond to different directions. The concordance is particularly important because the measurement routine at Näsudden was completely different from that of the eastern and the northern coasts.

The analysed data suggest that a specific large-scale structure of dominating winds indeed exists in the Baltic proper. The structure consists of frequent south-west and north winds and clearly less frequent and weaker east winds. Also, it has a well-defined secondary minimum corresponding to north-west winds. Literally speaking, the wind regime in the Baltic proper resembles an along-street wind. The dominating winds come either from the general direction of large-scale westerlies or match the axis of the obstacle-free area. Data from the adjacent areas suggest that this structure does not penetrate into the mainland nor into the Gulf of Riga, Moonsund or the Gulf of Finland (which mostly have a relatively low frequency of north winds; see Handbook, 1966; Köuts, 1998; Tomson and Hansen, 2000; Soomere, 2001b; unfortunately, detailed wind data from the coasts of Latvia and Lithuania are not available).

The wind regime at the higher levels at Näsudden (incl. the 38 m level used in the analysis above) apparently well represents that of the open sea. Comparison of scalar and dynamical wind properties at Näsudden and at Vilsandi shows that Vilsandi data also well represent open sea wind properties. Indeed, maxima of angular distribution of mean wind speed practically coincide (8.2 m/s at Näsudden, 8.0 m/s at Vilsandi for SW winds and 7.6 m/s at Näsudden, 7.3 m/s at Vilsandi for NNW winds). The frequency of occurrence of moderate and strong winds at Näsudden and at Vilsandi is practically identical (53–54% for wind speeds ≥ 6 m/s and 17% for wind speeds >10 m/s) whereas the Sõrve site is characterised by 58%/
Angular distributions of the frequency of winds, the mean and the maximum wind speed (Fig. 3a, b) are most similar at Näsuudden and at Vilsandi. They all have a two-peaked shape and the locations of peaks for both sites practically coincide. The maximum wind speed at Näsuudden is 22.8 m/s for NNW winds (Vilsandi 24 m/s) and 22.4 m/s (Vilsandi 25 m/s) for SW winds (Soomere and Kevvalik, 2001).

There is indeed some evidence of a mainland-caused screening effect in the analysed data. The fact that the secondary north peak of the angular distributions of the wind properties at Näsuudden is shifted in a westerly direction as compared to Vilsandi suggests that Gotland damps NNW-NNE winds to some extent. The remarkably low maximum east wind speed at Vilsandi (11 m/s, the global minimum of this distribution at Näsuudden is 15.6 m/s for NEE winds) apparently results from the screening effect caused by Saaremaa and Hiiumaa. A forest nearby evidently distorts the wind field at Ristna; in particular, the north peak in the angular distributions of wind parameters does not become evident (Fig. 2b). Wind data from Sõrve reveal features typical of the Gulf of Riga area and, in particular, contains a relatively high portion of southeast winds.

Thus, Vilsandi data well represent the wind properties in the northern Baltic proper for all directions except east. The estimates of frequencies of strong storms and their directional distribution, used in the wave regime assessments below, have been made on the basis of Vilsandi data. The damping of east winds

![Angular distribution of mean wind speed](image1)

![Comparison of measured maximum wind speed](image2)

Fig. 3. Angular distribution of (a) mean wind speed at Vilsandi (1977–1991) and Näsuudden (1980–1989); (b) comparison of measured maximum wind speed at Vilsandi (1977–1991) with estimated maximum of average wind speed for 6 hours once every 10, 20, 50 and 100 years.
is unimportant in the context of wave prediction in the coastal zone of Estonia because waves coming from the east and north-east are fetch-limited anyway.

3. Directional distribution of extreme wind speed

The anisotropy of strong winds demonstrated above results in significant angular variation of the mean and the maximum wind speed (Fig. 3a, b; cf. Bergström, 1992a,b; Mohr and Sandström, 1996; Soomere and Keevallik, 2001). The latter quantity is particularly important in estimates of maximum wave loads. Notice that it is irrelevant to use climatological values of the maximum wind speed (which may reach 35–40 m/s according to Handbook, 1966; Estonian Climate Atlas, 1969; Elken et al., 2000) for estimates of maximum wave heights and loads. Extremely high wind speeds mostly represent wind properties in short localised gusts but high waves may occur only if strong winds blow for several hours.

The available climatological data carry insufficient information about the angular structure of extreme wind speed in long-lasting storms. An appropriate tool for estimating this structure is the Weibull (Gnedenko) distribution, with the density function \( f(u) = ku^{k-1}b^{-k} \exp\left[\frac{-u}{b}\right] \), where \( u > 0 \) is the instantaneous wind speed and \( b, k \) are the shape and scale parameters, respectively, whereas the probability that wind speed exceeds \( U \) m/s is \( P_{u,U} = F(U) = \exp\left[-\left(\frac{U}{b}\right)^k\right] \). In the North European climate, the scale parameter \( k \approx 2.0 \), and the distribution is close to the Rayleigh distribution (Troen and Petersen, 1989; Mohr and Sandström, 1996). Notice that the parameters \( b, k \) for particular directions do not necessarily match those for all winds (Soomere, 2001b).

If each wind record at Vilsandi is assumed to represent mean wind properties for 3 hours, the probability \( P_{u,U} \) shows how often the mean wind speed for 3 hours exceeds \( U \) m/s. Mean wind speed of the strongest storm (lasting 3 hours) during a time interval of interest (10, 50, 100 years etc. and containing \( N \) hours) is a solution to the inverse problem of finding \( U \) from the condition \( P_{u,U} = 3/N \).

Re-analysis of the Vilsandi data by this technique first shows that wind speeds of 25 m/s or more generally occur once every 20 years. Wind speeds may exceed 26 m/s once every 50 years, and 27 m/s once every 100 years. Second, the directional distribution of extreme wind speeds turns out to be strongly anisotropic. Maximum NNW wind speed is 27 m/s once every 100 years, whereas maximum east wind speed is only 11 m/s.

The wind speed maxima recorded during 1977–1991 generally well match the maxima estimated by the procedure described for time intervals of 10 and 20 years (Fig. 3b). All the distributions have a two-peaked shape with similar peaks in SW and NNW directions, a local minimum in NWW-NW directions, and global minimum in the eastern sector. The largest mismatch between the recorded and the estimated extreme wind speed occurs for the north-easterly and southerly directions where winds indeed are damped by Saaremaa: recorded wind speed maxima are 2–3 m/s lower than the estimated values.

Comparison of 12 622 synchronous recordings during 1980–1989 at Vilsandi, Ristna and Näsudden shows that wind speed at Vilsandi and Ristna is fairly well correlated (correlation coefficient is 0.67; Soomere, 2001b). This is not surprising since the distance between the sites is about 60 km and the sites are located on the eastern coast of the Baltic proper. The relatively high correlation between wind speeds at Näsudden and Vilsandi/Ristna (0.43/0.37) indicates that wind speeds are frequently similar in radically different sites.

The mean difference in wind direction between Ristna and Vilsandi is 23°, between Vilsandi and Näsudden 42°, and between Ristna and Näsudden 46°. Correlation analysis shows that wind directions at Vilsandi and Ristna coincide as frequently as do wind speeds but wind directions in Gotland and on the Estonian coast are much less correlated than wind speeds, so comparison of wind directions of different sites apparently better identifies large-scale wind patterns. The highly negative correlation between differences of wind direction and wind speed at these sites shows that strong wind patterns in the Baltic proper are considerably more uniform than weak wind fields. Indeed, for wind speeds of > 10 m/s, wind directions at Vilsandi and Ristna practically always coincide whereas the mean difference of wind direction at Näsudden and Vilsandi is comparable with the angular resolution of measurements at Vilsandi.

Coherent wind patterns in the Baltic Sea are generally quite persistent although wind direction may...
change considerably. Surprisingly, such changes in wind direction often occur simultaneously (Soomere, 2001b). Such long-term coherence, which is not lost even during radical turns of the wind direction, does not resemble an along-street wind. This is particularly unexpected in the Baltic Sea, where mesoscale effects typically govern the wind field and the synchronous turns of the wind direction at separated sites are infrequent (Tomson and Hansen, 2000).

4. Wave climate of the northern Baltic proper

Favourable conditions for high wave generation in the Baltic Sea occur relatively seldom and maximum wave heights in the Baltic proper remain much below those of the open ocean. Owing to the described anisotropy of the wind patterns, extremely high waves are expected to occur more frequently in the northeastern part of the basin. It has been claimed that at the entrance of the Gulf of Finland waves could be as high as 17 m (Davidan and Lopatukhin, 1982). Fortunately, in reality such extreme wave heights are not reached. The maximum significant wave height (the average height of the highest 1/3 of waves) during the last two decades was 7.7 m measured on 14 January 1984 (Kahma, 2000a). Recalculation of the wave field in this area has demonstrated that a significant wave height exceeding 7 m has occurred only four times since 1961 (among them twice in December 1999; Kahma, 2000a). Thus, maximum significant wave heights once in a century are not expected to exceed 8.5 m.

The northern Baltic Sea is a challenge for wave modelling, because of the small scale of the basin and the adjacent bays, the complex shoreline and numerous islands. The third generation wave model, the WAM model (Komen et al., 1994), was probably first implemented in the Finnish Institute of Marine Research in 1992. It works with a full two-dimensional wave spectrum, includes main effects on ocean wave generation and dissipation, estimates nonlinear energy exchange between wave harmonics reasonably well, but does not take into account energy exchange in wave triads (which becomes effective in shallow water, Booij et al., 1999). Given the wave spectrum, it is straightforward to calculate properties of wave fields such as significant wave height mostly used for characterising the wave fields below. Formerly (apparently owing to problems with obtaining the correct wind forcing) the wave heights during the peaks of the storms were often under-predicted by a factor of two (Tuomi et al., 1999; Kahma, 2000b). In other areas, the same problems cause some regional models to suffer from considerable over-prediction (Cieslikiwicz and Herman, 2000). Only recently, have the predictions of coupled WAM-HIRLAM models been improved significantly (Tuomi et al., 1999).

Recently, Jönsson et al. (2002) have calculated wave statistics for the whole of the Baltic proper. They hindcast surface waves with the second-generation spectral wave model HYPAS forced by reanalysed wind fields for the year 1999 from the atmospheric circulation model HIRLAM. The model results show a strong temporal and spatial variation in the wave field due to the physical dimensions of the different basins and the predominant wind field. The spatial resolution of the gridded wave data is 11 km, which is adequate for the Baltic proper but insufficient for resolving wave fields in the smaller basins such as the Gulf of Finland.

Considerable efforts have been made towards estimating wave height occurring with a probability of 10% (occasionally called critical wave height). Davidan and Lopatukhin (1982) estimate that the probability of occurrence of waves higher than 3 m does not exceed 20%. For various parts of the Baltic proper this probability is even less. Mostly, the critical wave height does not exceed 3 m along the major ship lanes across the Baltic Sea (see Soomere, 2001a, and references therein).

5. Anisotropy of wave regimes in the vicinity of Saaremaa Island

The above description reflects wave climate in the central and northern parts of the Baltic proper, where the occurrence of high waves weakly depends on the angular structure of the dominating and extreme winds. For the coastal areas of interest, the established anisotropy of the wind field has huge consequences: in addition to purely geometrical parameters of, say, a harbour, the extreme wave loads as well as sheltering properties of breakwaters depend on the directional distribution of extreme wind speed in a particular location.
Generally, in the framework of wave climate studies and estimates of extreme wave loads, wind speed, direction and duration are equally important. However, in relatively small basins such as the Baltic Sea, the wave height is frequently fetch-limited. In particular, for the north-western coast of Saaremaa, the maximum fetch is about 200 km for north-west winds and only a few tens of km for north-east and east winds. Thus, the wave field becomes saturated relatively fast (6–8 h) even during heavy storms (Soomere, 2001a). Consequently, extreme wave properties for a particular location can be found from a set of runs with steady winds, because turning wind and fluctuating wind speed generally lead to decreased wave amplitudes (Komen et al., 1994). Another argument for using only steady winds is that more or less uniform storms in which wind speed and direction vary insignificantly over large areas for many hours frequently occur in the Baltic proper (see Section 2).

Traditionally, in calculations of extreme wave heights it is assumed that extreme storms may blow from any direction or, equivalently, that the angular distribution of maximum wind speed is isotropic (Jönsson et al., 2002). Wave regime then only depends on geometrical factors such as fetch length, bottom topography, properties of the coastal line etc. One might argue that this concept is invalid as soon as the directional wind structure is at hand. However, in many regions the heaviest storms are vortex-like and may blow from any direction. It is well known that climate warming is accompanied by an ever more frequent occurrence of localised storms whose directional structure does not necessarily match the climatological directional distribution of extreme wind speeds. Thus, it is still reasonable to estimate maximum wave loads during such events. Also, the directional wind statistics may have a large error, because the number of winds from a particular direction is much less than the total number of wind recordings.

As an application of the concept of directional wind anisotropy, the wave regime in the vicinity of the new deep harbour in Saaremaa was analysed in detail (Fig. 4). Three possible harbour sites were considered (Elken et al., 2001). The Undva site is located in the relatively small Uudepanga Bay and is fully open in a north-westerly direction. The Suuriku-Kuriku site is located between the Suuriku Cliff and the Kuriku Cliff at the entrance of the Tagalaht Bay and is open to winds from a wide northern sector. The Vaigu site in the inner part of the Tagalaht Bay is sheltered from western winds and open only to north and north-east winds.

Wave properties were computed with the WAM model. The bathymetry was based on data prepared by the Institut für Ostseeforschung (Seifert et al., 1995), with spatial resolution 1’ along latitudes and 2’ along longitudes. A coarse-resolution model with a regular grid (step 3’ along latitudes and 6’ along longitudes, 11545 sea points) was run for the whole Baltic Sea. In the vicinity of the harbour, the model was run on a nested grid (110*110 km, step 1’ along latitudes and 2’ along longitudes, resolution about 1*1 mile, 3277 sea points). Wave properties at the open boundaries of the nested grid were taken from the coarse runs (Soomere, 2001a).

The WAM model predicts maximum wave heights (corresponding to a maximum wind speed of 25 m/s once every 20 years) slightly exceeding 8 m in the open sea near the new harbour during south-western and north-western storms. These results agree well with the above-discussed results of measurements and calculations with the coupled WAM-HIRLAM model.
Assuming that the directional distribution of the extreme wind speed is isotropic, the severest wave regime occurs near Undva during extreme NW and N winds (Fig. 5). Significant wave heights in the central part of the Uudepanga Bay may reach 6.8 m for north-west winds and exceed 6 m during winds from a relatively wide north-western sector (285–360°). They may reach 5.5 m during west storms and 4 m during SWW storms.

Maximum wave heights at Suuriku-Kuriku (6.2 m) occur during NNW storms (345°). Wave heights exceed 5.5 m during north winds from directions 300°–30° (Fig. 5). Extreme wave heights at Suuriku–Kuriku are 0.5–0.8 m less than at Undva for all winds from the north-western sector owing to the screening effect of the Suuriku Cliff. Waves at Suuriku–Kuriku are somewhat higher than at Undva only during north-east and east winds but are generally less than 3 m owing to screening effect of Hiiumaa. At Vaigu, only north winds from a narrow sector (330°–45°) may generate waves up to 4–5 m high. Fetch length during east winds is a few km only and maximum wave heights do not exceed 1.5 m.

Fig. 5. Dependence of modelled significant wave height (numbers at isolines, m) at the harbour sites (from top to bottom: Undva, Suuriku–Kuriku, Vaigu) on wind direction (horizontal axis), wind speed (left column: 20 m/s, right column: 25 m/s) and duration (hours, vertical axis).
The probability of critical wave heights (3 m) near the harbour sites was found from a series of simulations with steady winds. In the calculations, the angular distribution of the frequency of wind occurrence was taken into account but the directional structure of maximum wind speed was ignored. Wave heights exceeding 3 m may occur if the wind speed exceeds 16 m/s. In the Uudepanga Bay, wave heights exceed 3 m with a probability of 1% in the case of winds over 16 m/s from a wide sector from west to northeast (270°–45°, Fig. 5). At Suuriku–Kuriku, wave heights exceed 3 m with a probability of 0.6% for an equally wide sector (but shifted somewhat to the east: directions 300°–75°) for wind speeds exceeding 17 m/s. The probability of critical wave heights in the Uudepanga Bay exceeds that near Suuriku–Kuriku mainly because north-west storms are more frequent than north-east storms. At Vaigu wave heights exceed 3 m with a probability 0.13% only for very strong north winds (> 19 m/s) from a narrow sector (directions 315°–25°).

The directional distribution of extreme wave heights was constructed on the basis of the estimates of the angular distribution of extreme wind speeds. Fig. 6 demonstrates striking anisotropy of the distribution of maximum significant wave heights occurring once every 20 years near the harbour sites. Waves as high as 6 m may occur in the Uudepanga Bay during extreme NNW winds (330°–345°). For other wind directions the wave heights rapidly decrease but are still over 3 m for west winds. The severest wave regime at the Suuriku–Kuriku site (5.5–5.7 m, NNW winds, 330°–345°) differs insignificantly from that in the Uudepanga Bay. The Vaigu harbour site has a milder wave regime than the other sites. It virtually needs no breakwater in the easterly direction because wave heights during east storms do not exceed 1 m. The same conclusion may apply for the Suuriku–Kuriku harbour site, where wave heights during extreme northeast storms are less than 2.5 m.

Four regions with anomalously high waves can be distinguished in the neighbourhood of the harbour sites (Fig. 4). Two are located near Hiiumaa and are associated with shallow areas at the Neupokojev Bank and the Koroljov/Puumetsa Bank. Wave heights in these areas are 0.5–1 m higher than in the open sea. A minor anomaly lies next to the Suuriku Cliff where wave heights may reach 7.2 m during extreme north or northwest storms, whereas open sea wave heights are about 6 m. Most probably, this anomaly does not become evident (and a surf zone will apparently emerge instead), because the underwater slope contains an abrupt step there but the model thinks it is regular.

The strongest and the most extensive anomaly occurs in the area of the Harilaiu Bank where wave heights may reach 10.5 m. Since wave periods do not increase, waves in this area are steeper than in the open sea. The anomaly becomes evident only in a certain phase of strong storms if wind speed exceeds 20 m/s for a long time and wave heights exceed 5 m. The exact location of the highest waves depends on the wind speed, direction and duration (Soomere, 2001a).
The anomalies emerge owing to topographic refraction of surface waves typically resulting in the tendency of wave crests to become parallel to the bottom isolines (equivalently, wave rays bend towards shallower water). If waves propagate above a regular sea mountain, they tend to converge. The effect resembles the focusing of light rays by an optical lens. It becomes evident only if the slopes of the sea mountain are regular and mild, otherwise waves break or lose their energy during interaction with bottom inhomogeneities.

6. Discussion

The overwhelming domination of winds along the axis of the Baltic proper is apparently not caused by general features of the large-scale circulation only. It probably encounters some direction-dependent boundary-layer effects such as low-level jets that, according to some authors (Mohr, 1997; Smedman et al., 1996), may also affect wind regime near the sea surface. The existence of prevailing directions of strong winds has enormous consequences in areas where wind activity plays an important role. In particular, the immense angular variation of extreme wind speed causes a strong dependence of the maximum wave load on the geometry of the coastal line as well as a strong variance of maximum wave heights in various parts of the Baltic proper.

The directional analysis of the wave regime at the proposed sites of the Saaremaa new harbour is an instructive example. It has frequently been speculated that of the possible harbour sites, the Undva site in the Uudepanga Bay has the severest wave regime (because it is open to the north-west, from which direction storms frequently blow) but the directional distribution of stormy winds actually has a deep minimum for this particular direction and the wave climate near Undva is similar to that of the other sites. Thus, severe wave regimes depend considerably less on fetch length (which varies from a few tens of km to about 200 km) than on the angular structure of wind in extreme storms.

The frequent occurrence of large-scale persistent wind episodes that may last several days—a consequence of the anisotropic wind regime in the Baltic proper—may dramatically influence wind wave generation since fluctuations in the wind direction generally lead to decreased wave heights (Komen et al., 1994). This may be one of the reasons why models frequently underestimate wave heights in the Baltic Sea (Kahma et al., 1997; Tuomi et al., 1999). An interesting application of the concept of highly anisotropic winds is connected with the absence of high waves from some directions. Beaches open to these directions may be vulnerable with respect to ship-generated waves, in particular, with respect to wash due to contemporary high speed ships that may cause abnormally fast destruction of beaches with low natural wave activity.

The remarkable wave height anomaly at the Harilaia Bank may constitute a major navigation risk in the vicinity of the Saaremaa new harbour. Dynamically, bottom refraction of surface waves is equivalent to wave refraction on spatially varying currents and wave rays generally turn in the anomaly area. The most dramatic outcome happens if wave rays touch each other and form a caustic. In such locations, wave energy may be reflected in the form of waves with extremely steep profiles (Shyu and Tung, 1999). Recent theoretical studies suggest that freak waves created by this mechanism may frequently occur in certain areas (White and Fornberg, 1998). It is unclear when they are generated, how effective they are, or how far they can propagate from the anomaly area (because a large increase of wave energy at that location suggests that waves will mostly break) but even the presence of an extensive surf zone at the major ship lane is fairly inconvenient.

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