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ANISOTROPY OF MODERATE AND STRONG WINDS IN THE BALTIC PROPER

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Abstract. It is shown that directional distribution of moderate and strong winds in the Baltic Sea area is highly 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 distributions of moderate and strong winds are identical on both sides of the Baltic Sea. The specific wind regime does not penetrate into mainland.

Key words: wind directions, wind speed, wind energy, Baltic Sea meteorology.

1. INTRODUCTION

Wind field in Estonia and in the adjacent areas has been traditionally interpreted as more or less directionally homogeneous one with a slight prevalence of west and south-west winds [1]. There are two major reasons for deviations of the directional wind distribution from the isotropic one. Firstly, west winds dominate in the global atmospheric circulation and the west geostrophic wind in the higher part of the atmosphere. Only during April–September, directional distribution of geostrophic wind has a secondary maximum at north-east and east winds [2,3]. Secondly, dominance of south-west winds in the Baltic and Scandinavian countries results from a specific feature of the large-scale air pressure field. Namely, during certain seasons, a large low pressure area exists next to Iceland (North Atlantic Low), and a high air pressure area covers a huge domain in the northern part of the Eurasian continent (Siberian High). These structures are relatively well defined in the winter season. The western peripheral area of the North Atlantic Low (in which south and southwest winds dominate) frequently covers the Baltic Sea and elucidates prevalence of southwest winds during late autumn and winter.

The prevalence of south-westerly winds in the local wind regime is only weakly expressed in traditional wind roses. For example, monthly wind roses in the Gulf of Riga area show larger frequency of south-west winds during relatively stormy seasons (August–December) than during the calm first half-year when weak or moderate south-east winds dominate [4]. Similar features have been noticed at Swedish measurement sites [3]. The secondary maximum of geostrophic north-east winds seldom becomes evident in the local measurements.

It is generally known that directional structure of moderate (6–10 m/s) and strong (over 10 m/s) winds differs from that of all the winds. Namely, in many measurement sites the wind roses of these winds are strongly anisotropic. In spectacular cases, the number of events of south-west strong winds during late autumn and winter months is up to five times larger than the number of events of strong east winds [1]. However, traditional annual mean wind roses are more or less isotropic. Frequency of wind events from different directions generally differs less than ±30%.

Other non-isotropic peculiarities of the directional wind distribution have been considered as exceptional. Prevalence of certain wind directions in the coastal zone of Lake Peipsi [5] as well as in the coastal area of the Baltic Sea has been interpreted as evidence of the screening effect of the mainland. Minor deviations of wind roses from their isotropic form have been described in many publications [4,6]. Typically, they have been associated with obstacles in the neighbourhood of the measurement sites. Perhaps the strongest evidence of the wind anisotropy is the historically well known fact that the strongest storms in Estonia blow from south-west or west. This peculiarity hardly, if at all, becomes evident in traditional wind roses which count the number of wind events and do not record wind speed.

Apart from the above reasons that break the isotropy to a certain extent, the concept of directionally homogeneous wind regime dominates in the Baltic Sea area. Indeed, the area is void of global or large-scale effects causing strongly anisotropic (at least, during certain time intervals) wind fields such as monsoon, passat, sirocco, or mistral and it serves as a prolongation of the North Atlantic storm track. Frequent occurrence of high-latitude cyclones gives birth to high wind variability in the whole Baltic region and the concept of directionally more or less homogeneous wind is a good first guess.

A possible reason for such delineation of directional variability of winds in Estonia is caused by various reasons (incl. political ones during the years 1940–1990, even the analysed data have not been available). Typically, only static wind characteristics (wind roses, annual and monthly mean wind speeds, etc.) have been published. Only recently, several wind characteristics have been studied to some extent from the viewpoint of alternative energy sources [7–9]. Climatological variability of the wind regime in Estonia and its trends have been considered, for example, in [10–12].

An attempt to have a detailed look at the dynamic wind properties has been recently made in [13] on the basis of one-year high-resolution wind measurements in Harilaid Islet in the Moonsund area (Fig. 1). The directional distribution of the "wind capacity" (equivalently, the directional distribution of moderate and strong winds) was found much more anisotropic than the traditional wind rose. Although such an anisotropy is unimportant for wind energy studies, it nevertheless is of fundamental importance, for example, in wind wave studies and studies of currents or ice.

Analogous investigations have been performed in Sweden [3,14]. Directional distributions of annual and monthly mean wind speeds demonstrate moderate anisotropy, comparable to that of traditional wind roses. Annual mean wind speed shows more or less isotropic nature at Ölands södra grund lighthouse and at Näsudden on Gotland. Almagrundet lighthouse (near Stockholm) wind data have two well-defined peaks, corresponding to south-west and north winds whereas the north peak is about 10% higher than the south-west peak. Mohr and Sandström [14] only mention that it is difficult to explain this peculiarity.

The need for detailed analysis of the rate and expression of anisotropy of wind climate in Estonia arose from the hydrodynamic studies connected with the new harbour in the western part of Saaremaa [15]. Since this harbour will be, at least partly, opened to western and/or north-western directions, it is necessary to correctly estimate strongest possible winds in order to reasonably predict highest possible waves coming from those directions. The anisotropy of dominating winds is essential in such estimates.

In this study, we describe some amazing properties of directional distributions of moderate and strong winds in the coastal area of Estonia and Sweden. It is shown that primary properties of the anisotropy such as prevailing winds, frequency of

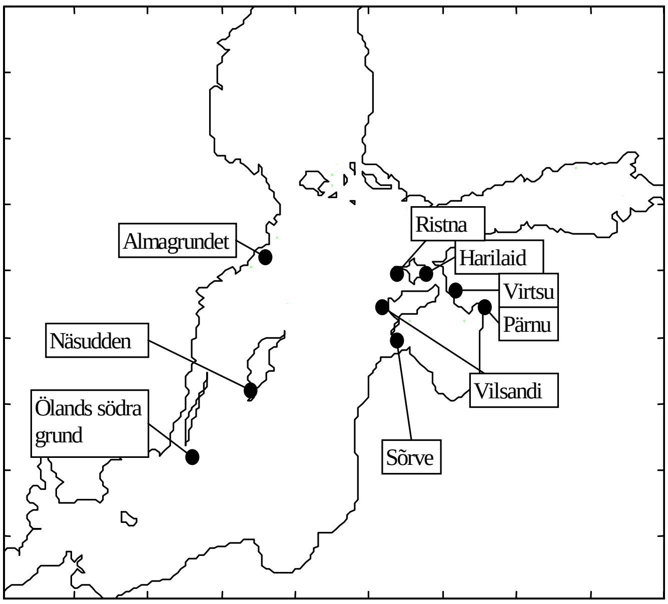

Fig. 1. Location of measurement sites.

their occurrence, and directional distribution of mean and maximum wind speeds are nearly identical on both sides of the Baltic Proper but greatly different in the measurement sites located in mainland. Finally, we indicate a possible phenomenon explaining this anisotropy and discuss several of its consequences.

2. ISOTROPY OF PLAIN COUNTING AND ANISOTROPY OF REAL WINDS

The analysis is based on 15 year long (1977–1991) data recordings at the Vilsandi and Ristna weather stations located at the eastern coast of the Baltic Sea (Fig. 1). In these sites, wind speed has been filed as an average over a 10-minute period at selected times (generally 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 GMT). The digitized data used below, however, contain only wind recordings at 0000, 0600, 1200, and 1800. The mean wind speed at Ristna was 4.25 m/s and at Vilsandi 6.4 m/s. In general, somewhat lower wind speed values were recorded at Ristna than at neighbouring weather stations. Most probably, the reduced wind speed is caused by a forest nearby.

The angular resolution of filing is 22.5° (16 directions). If only 8 directions were taken into account, the traditional wind rose would have been practically isotropic at both sites. If all 16 directions are used, deviation from the circular shape are of the order of 30% (Fig. 2). Such a simple count of wind events from different directions (which does not distinguish summer breeze from hurricanes) is not particularly informative because of serious physical reasons. It is well known that weak winds are mostly affected by the local situation. They represent actually stochastic fields and their properties resemble those of homogeneous turbulent fluctuations. Indeed, directional distribution of weak winds (50–70% from the total number of wind recordings) is perfectly isotropic.

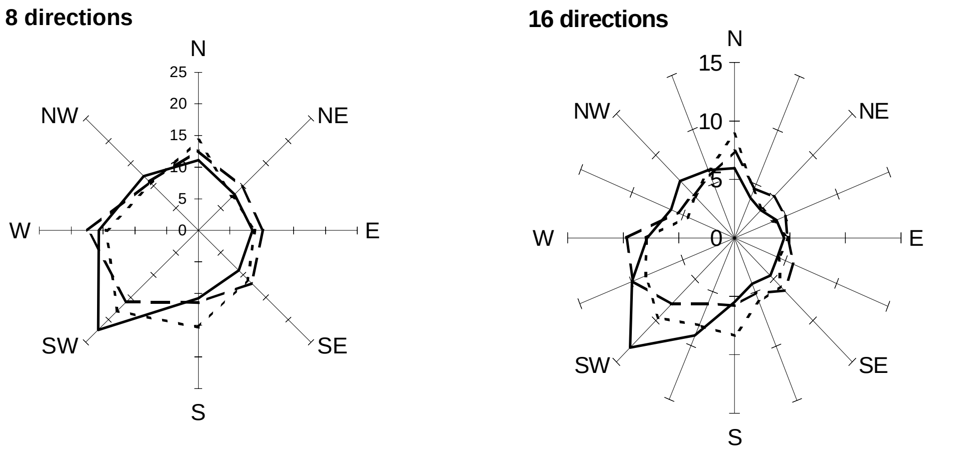

Fig. 2. Traditional wind roses for Näsudden (solid line), Vilsandi (dotted line), and Ristna (dashed line) measurement sites.

The situation changes drastically if one separates moderate and strong winds from the “background” of weak winds. For wind energy purposes, wind speeds under 5–6 m/s are unimportant [16]. Wind speeds under this value hardly may have any global importance and they are neglected also in wind wave studies [17].

The directional distribution of moderate and strong winds is surprisingly anisotropic. For Vilsandi it has a spectacular two-peaked shape. An extremely high peak corresponds to south-west winds and a somewhat lower peak – to north winds (Fig. 3a). At Ristna, no east winds exceeding 10 m/s were filed at all during the 15 years (Fig. 3b). The rate of anisotropy somewhat depends on the measurement site but typical contrast between frequency of wind events from different directions is more than 10 times.

Usually it has been considered that to have a representative climatology of strong winds, an observation period of 20–25 years is necessary. Nevertheless, we are of the opinion that such an anisotropy exists. The total number of analysed

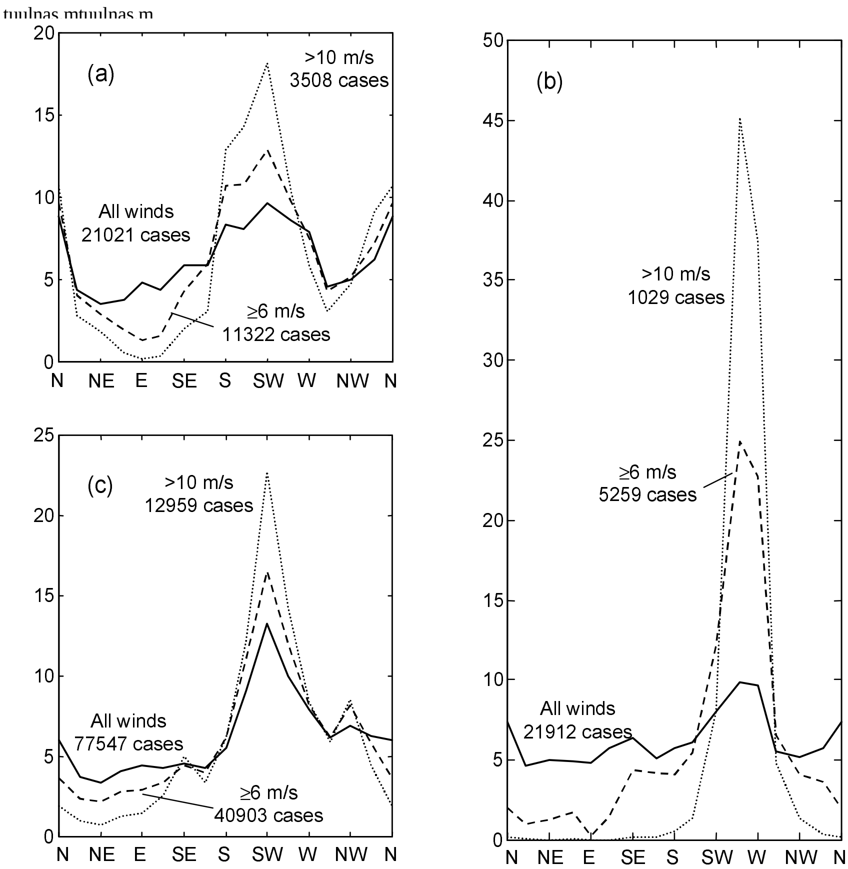

Fig. 3. Directional distribution of all winds (solid line), wind events with wind speed ≥6 m/s (dashed line), and strong winds (dotted line): (a) Vilsandi 1977–1991; (b) Ristna 1977–1991; (c) Näsudden 1980–1988, at 38 m level. Vertical axis represents relative frequency of occurrence of wind events, %.

wind snapshots is about 21 000 at both sites. Wind speed ≥ 6 m/s occurred about 11 000 times at Vilsandi and more than 5000 times at Ristna. Thus, the possibility of artificial peaks occurring owing to small number of measurements is excluded.

Figure 4 demonstrates that the two-peaked distribution of moderate and strong winds events exists during all seasons at Vilsandi whereas the location of both peaks is fixed. These features suggest that the shape of the distribution cannot be taken as an evidence of any of the above-considered anisotropic features of global circulation. It is also interesting to note that south-west winds do not

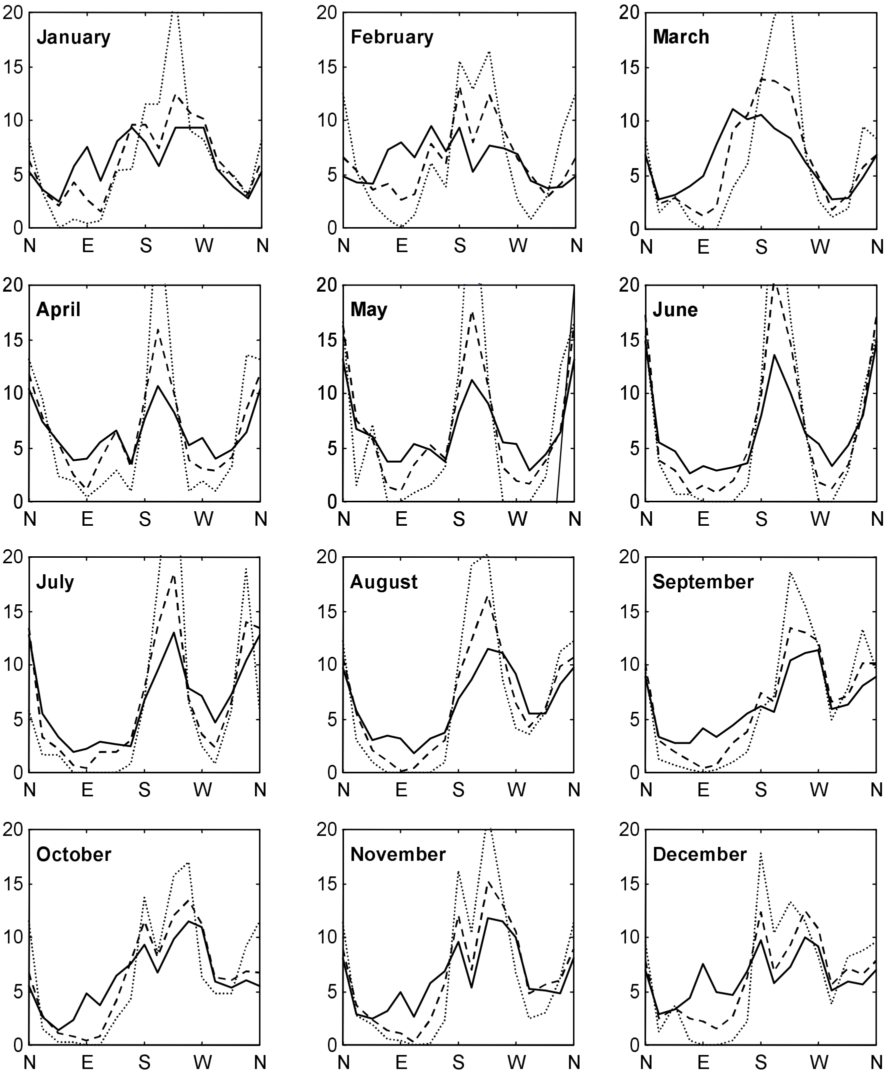

Fig. 4. Seasonal variation of the angular distribution of all wind events (solid line), wind events with wind speed ≥6 m/s (dashed line), and strong winds (dotted line) at Vilsandi (1977–1991); vertical axis represents relative frequency of occurrence of wind events, %.

dominate in the distribution of all winds during winter season at Vilsandi. This feature also deserves some attention since, typically, south-west winds dominate during winter season in the Baltic Sea area.

The anisotropy is not related to the possible screening effect of the mainland, located in the eastern direction from Vilsandi and Ristna. Since the Vilsandi measurement site is open to the sea (to the western direction), the local minimum corresponding to north-west winds is highly interesting and apparently is not caused by an obstacle. The absence of the minor peak, corresponding to the north winds in Ristna, evidently is caused by a forest nearby.

3. DIRECTIONAL DISTRIBUTION OF EXTREMAL WIND SPEEDS

The above has shown an impressive anisotropy of frequency of strong wind events. However, in terms of plain counting, this feature does not cause significant divergence of the mean wind speed from different directions. Figures 5 and 6 show that angular distribution of annual mean wind speed is qualitatively similar with that of strong wind events. The quantitative deviations of the wind speed are about ±30% from the mean value. The fact that deviations of this distribution from isotropy are moderate is not surprising. The number of strong wind events is about 1/6 from the total number of measurements but wind speed in the events is only 2–3 times higher than the mean wind speed. Thus, relative weight of these events is somewhat reduced in the plain count. Indeed, if one counts wind energy (proportional to wind speed squared) or capacity of a wind power generator (proportional to wind speed cubed within certain range of wind speeds), the result appears much less uniform.

The most drastic anisotropy becomes evident in the distribution of maximum wind speed from different directions (Fig. 6). Such description of the wind field is perhaps necessary in a small number of applications in mainland but critical in wave prediction, in particular, in estimates of maximum wave loads. The maximum filed wind speed at Vilsandi was 25 m/s (south-west storm on

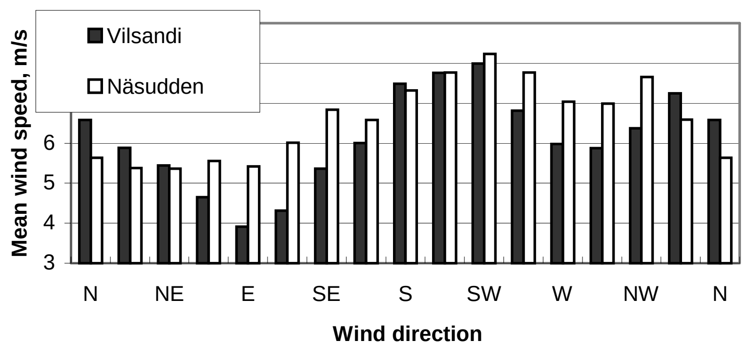

Fig. 5. Angular distribution of mean wind speed at Vilsandi (1977–1991) and Näsudden (1980–1988).

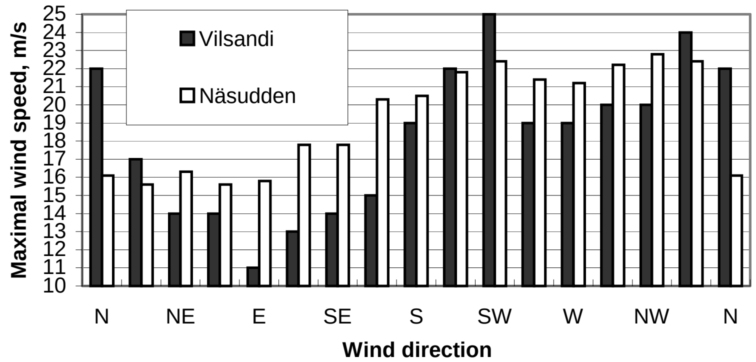

Fig. 6. Angular distribution of maximum wind speed at Vilsandi (1977–1991) and Näsudden (1980–1988).

27 February 1990, at noon) whereas the maximum east wind speed filed during 15 years (1977–1991) was only 11 m/s! One might argue whether the actual maximum east wind speed is that low. There is some evidence that east winds are damped to some extent near the measurement site (Fig. 7 shows how open are the sites for different wind directions).

The angular distribution of the maximum wind speed is similar to the distribution of the mean one (Figs. 5 and 6). Both distributions have two-peaked structure whereas locations of the peaks practically coincide. Notice that this similarity is not necessarily natural since the strongest wind speeds in many other areas are caused by hurricanes and may correspond to any geographical direction. Also, in [13] it has been shown that distributions of the mean wind speed, frequency of wind events, and relative energetic capacity all have different angular structure in the Moonsund area.

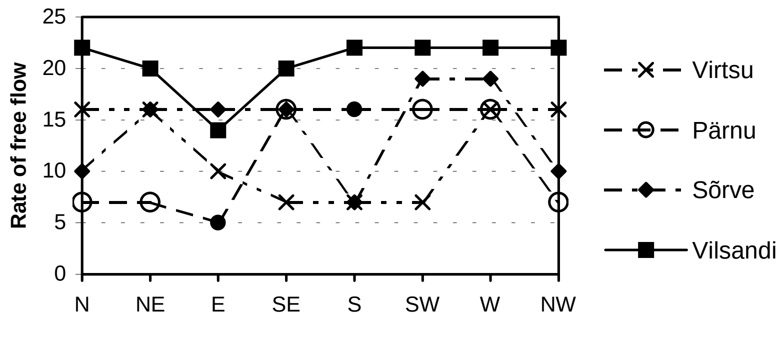

Fig. 7. Angular distribution of the rate of free flow at measurement sites in Estonia [10]; maximum rate is 25 (no obstacles nearby) and minimum 0 (for example, measurement site is located in a small field in a forest).

4. SIMILARITY OF WIND REGIMES AT THE EASTERN AND THE WESTERN SIDE OF THE BALTIC SEA

The described anisotropy apparently cannot be caused by the reasons discussed in Introduction since it contains specific “fine” structure in the form of relatively low frequency of north-west winds and high frequency of north winds. Also, it exists during summer months when the global air pressure distribution generally does not support south-west winds.

The anisotropy can be reformulated in terms of essentially reduced frequency of moderate and strong east winds, in particular, during summer months. The first guess to explain such a strong anisotropy at Vilsandi and Ristna is to refer to the screening effect of the mainland. This factor, in principle, may essentially damp east winds at the eastern coast of the Baltic Sea. As for the western coast, it is natural to expect that a mirrored feature should occur, i.e., west winds should be damped and relative intensity of east winds increased to some extent. Since the Swedish coast is oriented in SSW-NNE direction, the conjecture means that the wind roses from the Swedish coastal zone should reveal much higher portion of winds from the eastern sector and decreased relative strength of north-west wind events as compared to wind roses of Saaremaa and Hiiumaa.

Surprisingly enough, wind roses constructed on the basis of earlier data (for example, measured at Ölands södra grund on 1961–1970 and 1982–1989 and at Almagrundet on 1976–1995) show a deep minimum of east winds (except in April which is the most calm month [[3,14]]). Moreover, the wind roses of Sweden show even smaller portion of east and south-east winds at the western coast of the Baltic Proper as compared to the eastern coast. They also reveal a well-defined maximum for west winds and optionally (during the relatively calm period) a secondary peak for north-east and east winds. During stormy periods, another secondary peak corresponding to north winds appears.

This directional distribution cannot be explained by penetration of geostrophic winds into the lower atmosphere. Geostrophic winds in Sweden and Denmark have a global maximum for west winds and generally a deep minimum for north winds [[2,18,19]]. A minor maximum for north-east and east winds only exists during April–September [[2]]. Thus, domination of westerlies in the measured wind data may result from the overwhelming domination of west winds in the geostrophic wind. However, occurrence of other wind events (in particular, secondary maximum for north winds) is rather anticorrelated with the geostrophic wind.

In order to have a closer look at the wind regime on the western coast of the Baltic Sea, high-resolution wind data measured at Näsudden (southern coast of Gotland), during eight years (1980–1983 and 1985–1988) were analysed. Wind speed had been measured continuously at seven different heights (10–140 m) and filed as an average over a few minutes. Wind direction was also measured with an accuracy of a few degrees at three heights and filed as an average over a certain time period. In what follows, wind data on the 38 m level was used because annual mean wind speed value was closest to the mean wind speed at Vilsandi.

The traditional wind rose (including weak winds) at Näsudden is more anisotropic than those at the Estonian sites (Fig. 2). Notice that wind rose with 8 directions shows a very limited difference between three sites in question and totally smoothes out anisotropic nature of stronger wind events. Wind rose with 16 directions represents a relatively wide peak for south-west winds. Their frequency exceeds for three times the frequency of east winds. The relatively anisotropic shape of the traditional wind rose as compared to wind roses of Vilsandi and Ristna is evidently caused by a small number of weak winds at Näsudden.

The directional distribution of moderate and strong winds is again strongly asymmetric. It has two peaks. The main peak corresponds to south-west winds and the minor peak – to north-west winds. The distribution of strong winds is totally asymmetric, with two maxima similar to the just described ones. The positions of the main peaks at Näsudden and Vilsandi exactly coincide. The directional wind distribution at Ristna has no secondary peak for north winds, apparently due to a forest near the measurement site. The shift of the main peak at Ristna by 22.5° (one step in angular resolution) in the western direction probably is due to the screening effect of Saaremaa. Relatively low frequency of north winds at Näsudden (causing shift of the north peak to the western direction) apparently results from the screening effect of Gotland, since data from Almagrundet and Ölands södra grund show a well-defined peak for north winds [[14]].

Angular distributions of the mean and the maximum wind speed (Figs. 5 and 6) are most similar at Näsudden and Vilsandi. They both have two-peaked shape, whereas the locations of maxima for both sites practically coincide. In both distributions, the secondary peak at Näsudden is somewhat smoother and slightly shifted to the western direction as compared to Vilsandi. This parallelism is not limited to qualitative similarity only. Frequency of occurrence of south-west winds is nearly identical at both sites. Mean wind speed at Vilsandi is 6.4 and at Näsudden 6.9 m/s. Maxima of angular distribution of mean wind speed practically coincide (8.2 m/s at Näsudden and 8.0 m/s at Vilsandi in the case of SW winds, and 7.6 m/s at Näsudden and 7.3 m/s at Vilsandi in the case of NNW winds).

Thus, comparison of the directional distributions of wind parameters demonstrates amazing concordance between wind regimes at the opposite sides of the Baltic Proper. The concordance is particularly important because the measurement routine at Näsudden was completely different from that at Vilsandi and Ristna. At Näsudden, actual wind dynamics (averaged over one hour periods) was continuously measured whereas at Vilsandi and Ristna 10-minute snapshots of wind speed and direction were recorded several times per day.

A basically nontrivial feature of the presented data is that peaks of the directional distribution are located at the same direction at both sides of the Baltic Proper. If the directional anisotropy was caused by screening effect of the mainland, the minima of the distributions should correspond to different directions. Mainland-caused distortions should damp easterly winds in Saaremaa and Hiiumaa but westerly winds at Swedish measurement sites. Comparison of Figs. 3a, b, and c as well as of Figs. 5 and 6 show concordance of the wind regimes in diametrically different sites.

There is, however, some evidence of the screening effect caused by the Scandinavian and Estonian mainland. It becomes evident in angular distributions of the mean and maximum recorded wind speeds (Figs. 5 and 6) where Näsudden data reveal somewhat less variance. Wind speed maxima are 22.8 m/s in the case of NNW winds (Vilsandi 24 m/s) and 22.4 m/s (Vilsandi 25 m/s) in the case of SW winds. The global minimum of this distribution is 15.6 m/s in the case of NEE winds (Vilsandi 11 m/s, east winds). From this comparison it becomes clear that east winds are generally weaker at Vilsandi and that Gotland damps NNW-NNE winds at Näsudden to some extent. There is no evidence of damping of NW winds at Näsudden.

Still, the variance of angular distribution of maximum recorded wind speed at Näsudden is huge from the viewpoint of wind wave prediction. North-east and east winds have not exceeded 15.6 m/s. Thus, maximum wave height in the coastal zone of Sweden during north-east storms is limited by 2.5 m. West wind, however, may frequently blow 22–23 m/s and excite waves over 5 m in the coastal zone of Saaremaa and Hiiumaa.

Comparison of the distributions of the wind events, maximum and mean wind speeds at Näsudden and Vilsandi shows that Vilsandi data are highly reliable for all directions except east. Näsudden data apparently are distorted to some extent for north winds. However, the mainland-caused effects on the directional distributions of wind parameters are inferior as compared to the dominating wind regime.

Comparison of wind regimes in Swedish and Estonian coastal areas indicates that a specific large-scale structure of dominating winds exists in the Baltic Proper. The structure consists of frequent and strong south-west and north winds and clearly weaker east winds, and reveals a well-defined secondary minimum corresponding to north-west winds. Data from the adjacent areas suggest that this structure does not penetrate into the mainland (cf. [4,13,19] and Fig. 8, extracted from [10]). The main difference between wind regimes of the Baltic Proper and the adjacent areas consists in a low frequency of strong north winds in mainland, Moonsund, and Gulf of Riga. A moderate peak corresponding to north winds at Virtsu (Fig. 8) apparently is caused by the fact that this measurement site is mostly opened to the north. Data from Moonsund area demonstrate domination of south winds among all wind events and a wide maximum covering all western directions in the angular distribution of wind power capacity [13]. Unfortunately, detailed wind data from the coastal area of Latvia and Lithuania are not available.

These facts suggest that wind regime in the Baltic Proper is somewhat similar to that in a wide street since the dominating winds come either from the general direction of global westerlies or match the axis of the obstacle-free area. However, the concept is only conditionally applicable since the dominating directions relatively poorly match the axis of the Baltic Proper.

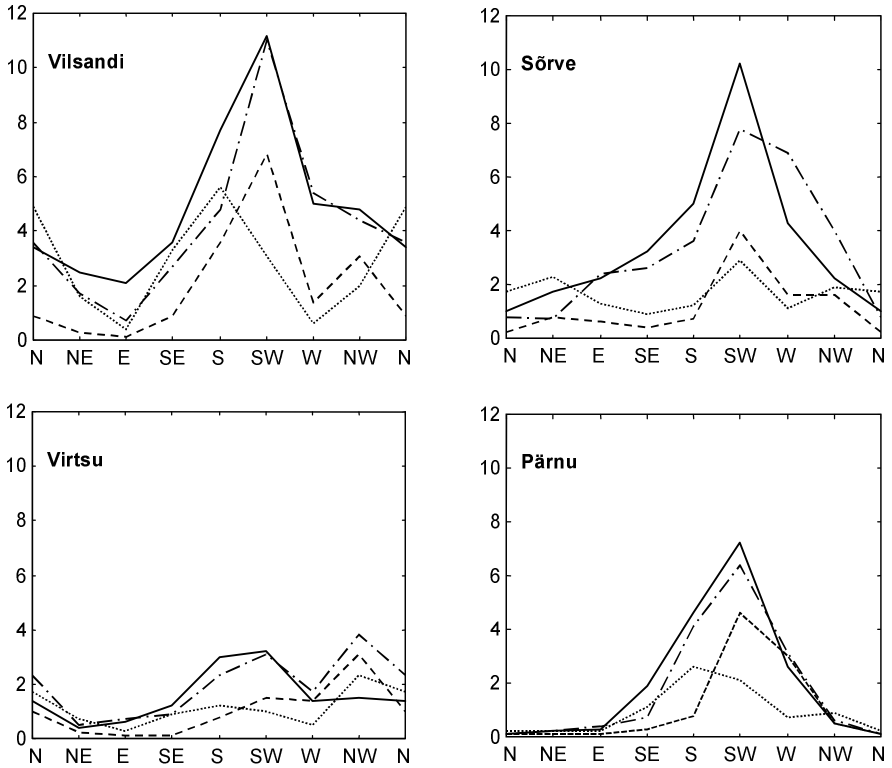

Fig. 8. Directional distribution of strong winds during different seasons in historical data (1950–1960) at Vilsandi, Sõrve, Pärnu, and Virtsu weather stations [10]. Solid line corrreponds to January, dotted line to April, dashed line to July, and dash-dotted line to October. As different from Figs. 2–4, the frequency of occurrence of strong winds among all wind events is presented, %.

5. DISCUSSION

The above has shown that overwhelming domination of winds along the axis of the Baltic Proper apparently is not caused by general features of the global circulation only. Consequently, it probably encounters specific direction-dependent boundary-layer effects. Among them, the most delicate mechanism is connected with the frequent existence of low-level jets in the area in question [20]. Numerical experiments [21] demonstrate that geostrophic wind, blowing along the axis of the Baltic Proper, may be amplified up to 2.5 times when a low-level jet emerges whereas the wind blowing across the basin is amplified only by 30%. This peculiarity partially explains the overwhelming domination of the south-west winds in the above distributions and the low frequency of east winds.

The prevailing direction of moderate and strong winds in the Baltic Proper (as well as in any other region) has enormous consequences in areas where wind activity has to be taken into account. A primary area of importance is constructing harbours or wave-protecting moles. Wind waves typically propagate in the direction of the wind. If dangerous waves are restricted to a single direction, it is relatively inexpensive to protect harbour areas or beaches against high waves.

The high anisotropy of directional wind distributions and their coinciding shapes over a large area suggests that relatively homogeneous storm events might be frequent in the Baltic Proper. The influence of events of spatially constant wind on the wind wave generation may be dramatic since fluctuations in the wind direction generally lead to fast decrease in the wave height [17]. Parameters of wave generation are normally measured during typical (fluctuating in speed and direction) wind regimes. Events of spatially constant wind may be one of the reasons why standard third-generation wave models underestimate (at times by a factor of two) wave height during short storms [22,23].

Another interesting issue becomes evident if the described features are applied for estimates of highest possible wave regimes in certain areas. Perhaps the most intensive coastal zone studies during the last years have been performed in connection with the new harbour in the north-west coast of Saaremaa [15]. It has been frequently speculated that Uudepanga Bay has the toughest wave regime among theoretically possible harbour sites since it is opened to north-west and storms frequently blow from this direction. The directional distribution of stormy winds actually has a deep minimum for this particular direction! Quantitatively, the south-west storms are six times more frequent and the north storms three times more frequent than the north-west storms.

A more delicate 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 extremely vulnerable with respect to ship-generated waves, in particular, with respect to wash due to high speed craft traffic [24]. Ship waves may cause abnormally fast destruction of beaches located in areas with low natural wave activity. The provided analysis shows that beaches open to the eastern direction generally are most vulnerable to ship wash.

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MÕÕDUKATE JA TUGEVATE TUULTE ANISOTROOPIA LÄÄNEMEREL

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On näidatud, et mõõdukate ja tugevate tuulte jaotus Läänemerel on ilmakaarte järgi anisotroopne. Tugevate tuulte seas domineerivad edela- ja põhjatuuled, loodetormid esinevad palju harvemini ning kirde- ja idatormid väga harva. Läänemere lääneranniku tuulte peamiste parameetrite jaotus ilmakaarte järgi on identne vastava jaotusega Saaremaal ja Hiiumaal. Läänemere avaosale iseloomulik tuulte jaotus ei ulatu kaugele sisemaale.