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Seasonal and diurnal variations of wind parameters at Pakri

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Abstract. Long-term, seasonal, and diurnal variations of the wind speed in 1969–1992 are analysed for a homogeneous wind data set from Pakri, located on the North Estonian coast in the western part of the Gulf of Finland, the Baltic Sea. Interannual variations of the annual mean wind speed are mostly ±1 m/s from the overall average (5.1 m/s). Seasonal variations of the monthly mean wind speed have the same magnitude. No clear trend in the annual mean wind speed existed in 1966–1992 and a drastic drop in the respective value in 1993 stems from the relocation of the measurement site. Wind speed frequency distributions vary during the year showing the largest seasonal differences for west and north-west winds. While there is almost no dependence of the wind speed on the measurement time in winter and in autumn, there is a large daily cycle in spring and summer with values deviating by ±0.75 m/s from the average.

Key words: wind speed, periodic variations, diurnal cycle, marine winds.

1. INTRODUCTION

Statistical properties of wind fields over marine and coastal areas are of great importance for several practical tasks. This information becomes especially vital in Estonian nearshore waters where a complex interplay of the large-scale air flow with surface roughness and the presence of large-scale features such as the North Estonian klint cause substantial inhomogeneity of average wind properties in different coastal areas [1,2], and where the mismatch of the orientation of coastline and the dominant direction of the geostrophic flow give rise to specific phenomena such as low-level jets along the coastline [3] (strong, apparently channelled easterly winds along the central part of the Gulf of Finland during certain seasons), or mismatch between directions of the most frequent and strongest winds [2]. For practical questions, these features become important in terms of anisotropy of different wind-induced phenomena, such as for the anisotropy of wave fields [4] that may play a decisive role in the planning of harbours and coastal engineering structures [5] or problems connected with the estimation of the wind and wave energy potential [6] and wind farm planning.

Historically, the wind field in Estonia has been treated as practically homogeneous with a slight prevalence of west or south-west winds. This directional anisotropy stems from the domination of a large-scale western airflow at these latitudes [7,8]. The basis of this assumption is that the majority of the classical wind roses (that equally account for all wind measurements notwithstanding the wind speed) are almost circular, with a slight prevalence of wind from certain directions [2,7–9]. On the other hand, the wind roses for moderate and strong winds (over 5 m/s) are highly anisotropic [2,10,11]. This feature suggests that the more or less isotropic shape of traditional wind roses apparently is caused by the relatively long periods of weak winds that are either of local origin or occur when the large-scale flow has been substantially distorted.

Both historical data and more recent studies demonstrate that the dominating wind direction in the region of the Baltic Sea is south-west. Over the northern Baltic Proper, a secondary peak corresponds to winds from the northern sector (for example, from the NNW direction, following the axis of the open sea contours). The particular appearance of the corresponding peak in the wind rose and the potential maximum speed for such winds is somewhat different for different measurement sites [11]. On the other hand, the angular distribution of strong winds has a significant minimum for east winds and a smaller minimum for north-west winds [10]. There is evidence that the wind regime in sub-basins of the Baltic Sea surrounding Estonia considerably differs from that in the Baltic Proper. For example, the wind regime of the Gulf of Finland (Fig. 1) combines the dominating south-west winds with local east and west winds blowing along the axis of the gulf whereas the proportion of north winds, which is notable in the

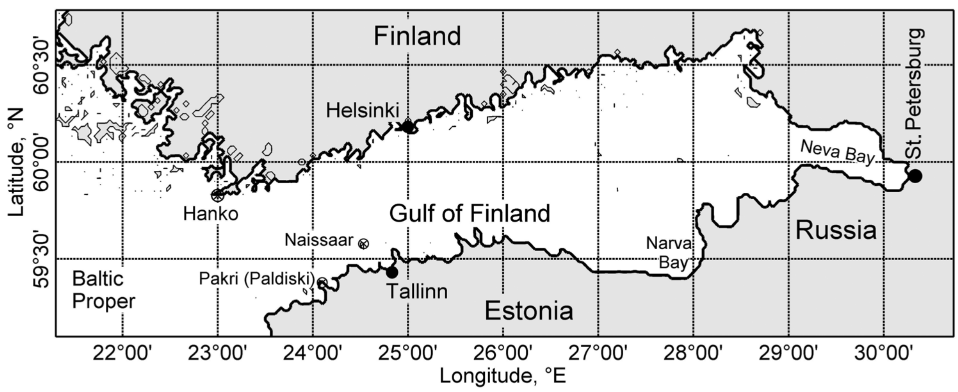

Fig. 1. Location of wind measurement sites in the Gulf of Finland.

western part of the gulf, reduces considerably in its eastern part [2]. The most interesting feature for the winds over the Gulf of Finland is that the angular structure of strong winds does not match the structure of all winds: strong winds frequently blow from directions where winds generally are infrequent. Another interesting feature of wind patterns in this area is that even relatively well-placed and fully open wind measurement sites in the coastal area of the Gulf of Finland do not represent many important properties of marine winds [1,12,13].

The listed features suggest that the estimates of wind properties in the coastal areas of Estonia should be made with great care and with the use of information about the subtle features of the local wind regime. This concern particularly applies to the nearshore of northern Estonia in which the wind in coastal sea areas, which usually blows from SW, may undergo substantial modifications owing to large-scale topographic features along the Estonian coast. These features may considerably affect not only the instantaneous values of wind properties but also the periodical (annual and diurnal) components of the wind speed that are highly site-specific in this area [2,14] and the potential variation of which is vital for planning offshore wind farms in the southern part of the Gulf of Finland.

In this paper, this analysis is undertaken for the Pakri meteorological station that is the closest to the planned location of a large wind farm site near the Estonian coast. First, we analyse the extent of interannual variations of wind properties and seasonal and short-scale periodic variability in the wind speed. Second, we estimate the probability of the occurrence of instantaneous wind speed exceeding a certain value in different seasons and the frequency of strong winds blowing from different directions.

2. DATA

Wind properties have been systematically measured on the Pakri peninsula since 1886, but the measurement routine, apparatus, and the location of the site has changed several times since then. These changes are reflected in seemingly drastic changes in the wind properties, which make the older wind data (before 1966) unusable for the analysis in question.

Data, measured during the latter decades, also suffer from changes of the routine. While introduction of anemorhumbometers instead of wind vanes in 1981 led to a slight decrease in the recorded average wind speed, the relocation of the measurement site led to a substantial change of the annual mean wind speed. The annual mean wind speed for the years 1966–1969 was 5.14 m/s, only slightly smaller (5.07 m/s) for the years 1970–1992, after moving the station into the vicinity of the town, but considerably lower (3.26 m/s) for the years 1993–2000, after the station was moved to a much more sheltered site (Fig. 2). While there apparently was no clear trend in the wind speed in 1966–1992, a drastic drop in the annual mean wind speed from 1993 evidently stems from the relocation of the site.

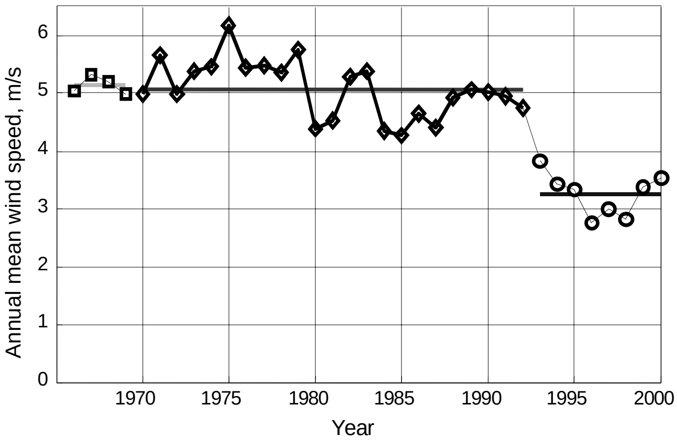

Fig. 2. Annual mean wind speed at Pakri for 1966–2000. The horizontal lines indicate the mean wind speed in 1966–1969 (squares), 1970–1992 (rhombuses) and 1993–2000 (circles).

The longest basically homogeneous data set is from October 21, 1969 to December 14, 1992. During this period the measurement field was situated on the high bank near the western border of the town of Paldiski, 160 m from the coastline. The observation field was fully open to the directions from SW, W, NW, N, and NE and somewhat restricted to directions from E to S. The wind sensor was exposed, situated higher than surrounding obstacles (very low buildings) at the distance of 60–100 m from the measurement site. The coordinates of the station were 59°21′18″N, 24°03′07″E and the altitude of the measurement field was 13 m above the sea level. During this period, wind speed and direction were measured eight times per day, at 00, 03, 06, 09, 12, 15, 18 and 21 GMT. The measurements were carried out at the standard height over the measurement field of 10 m.

Until 1980, the wind parameters were measured by means of the wind vane. Wind direction was registered in a 16-rhumb system. Since 1981, the measurements were continued using an anemorhumbometer, from which time the wind direction was registered with an accuracy of 10 degrees, that is, in a 36-rhumb system of direction. To make earlier data comparable with the later, measurements in the 36-rhumb system were reduced to the 16-rhumb system using an appropriate algorithm [[1,12]]. A certain decrease in the annual mean wind speed (Fig. 2) since 1981 may partially stem from the change in the apparatus, but the decrease is minor and does not affect the results of our analysis.

For reference, data recorded at the islands of Naissaar and Hanko were used (Fig. 1). Naissaar meteorological station was located on the northern cape of the island (59°36′N, 24°31′E), just at the entrance of Tallinn Bay. This station was closed in 1992. Therefore, data during the period November 1969–December 1991 were used. The altitude of the station was 2 m and it was open to the sea from W over N to NE and sheltered by forest in the S and SE. The wind speed was measured with a resolution of 1 m/s for weak winds and with a resolution of

2 m/s for strong winds. The wind direction was recorded in the 16-rhumb system. During most of the observation period, the recordings were performed 8 times a day, but there were shorter time intervals when measurements were performed 4 times a day. The measurement height was 12–13 m from the surface. Hanko (59°49′N, 22°59′E) is situated on the northern coast of the Gulf of Finland and is operated by the Finnish Meteorological Institute. The measurement routine is basically similar to that at Pakri. The data from this site represent well the features of the wind field in the open part of the northern Baltic Proper and also the specific features of the wind regime in the Gulf of Finland. Data from October 21, 1969 to December 14, 1992 are used in the comparison.

3. PERIODIC VARIATIONS OF THE WIND SPEED

The average wind speed at Pakri during the 23-year period of November 1969–October 1992 was 5.07 m/s. The deviations from this mean value were generally less than ±1 m/s (Fig. 2). The windiest years were 1975 and 1979, with the annual mean wind speed of 6.18 m/s and 5.75 m/s, respectively. The calmest years were 1984 and 1985 when the average wind speed was 4.34 m/s and 4.26 m/s, respectively. At the reference sites, the annual average wind speed was comparable with that at Pakri: 5.04 m/s at Naissaar and 6.04 m/s at Hanko.

The annual cycle of monthly average wind speed shows fairly large seasonal variation, the appearance of which is typical for the Estonian coastal measurement sites [2,10], with minimum values in mid-summer (June–July) and maximum values during late autumn and early winter (November–January, Fig. 3). The same can be said about the annual cycle of the wind speed at Hanko and Naissaar (not shown in this paper). This feature apparently exists for the entire Baltic Sea region and reflects the seasonal variability of cyclone generation over the North Atlantic [15].

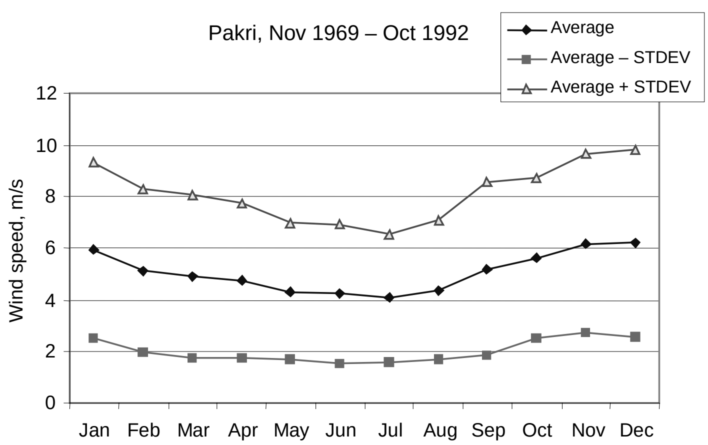

Fig. 3. Monthly average wind speed and its standard deviation.

There is evidence showing a seasonal variability of the mean vertical shear of the air flow at different heights [16,17]. The nature and magnitude of this variability, however, has not been quantified as yet. It may reflect the variations of the direction of the air flow in the upper layers [18] which would lead to the transport of air masses over areas with different surface roughness during different seasons.

The spectrum of shorter variations (from one year down to a few days) of wind speed in the coastal zone of Estonia has no clearly expressed periodic components [17]. This feature matches the analogous property of water level along the Estonian and Finnish coasts [13].

There is, however, a strong periodical signal in the wind data from the Estonian coastal wind measurement sites – a considerable diurnal variation of the wind speed [2]. This feature is traditionally associated with the presence of the mainland where the difference in the temperatures of the air masses and the underlying surface is large, and almost periodic. In coastal conditions, the sea breeze and the low-level jets [3] may contribute to this variability. This feature is much less pronounced, if evident at all, in marine conditions where the diurnal variations of the sea surface temperature are much smaller. The relative amplitude of this cycle with respect to the mean wind speed has been interpreted as a criterion of the ability of wind recordings to reflect the properties of offshore winds at a particular coastal site [2].

The amplitude of the daily cycle of the wind speed substantially changes in different seasons (Fig. 4). While there is almost no dependence of the wind speed on the measurement time in winter and a weak maximum becomes evident at midday in autumn, there is a strong daily cycle in spring and summer. Such a variation is similar to that observed at Swedish wind measurement sites [19].

A part of this cycle is obviously due to the local sea breeze. The analysis of the directional distribution of winds at different time instants, however, suggests

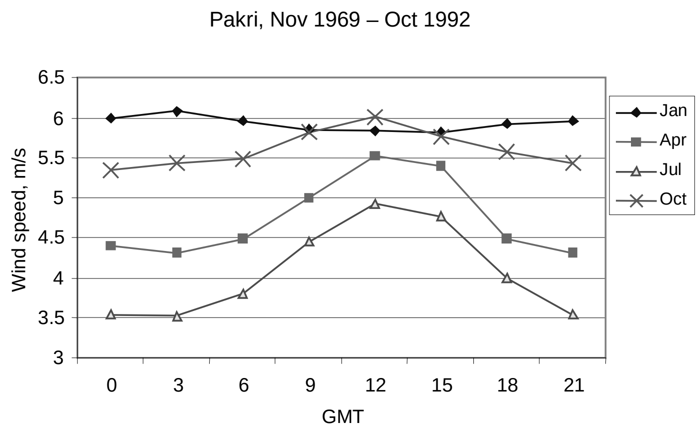

Fig. 4. Diurnal cycle of the wind speed in different seasons.

that the dominance of daytime winds over night winds that is characteristic of mainland measurement sites also contributes to this feature. Moreover, analysis in [20] suggests that, at the UK coasts, winds with a land fetch have a pronounced diurnal cycle in wind speed in spring, summer, and autumn whereas there is a very weak diurnal cycle for winds with a sea fetch. As at Pakri, wind speed has no diurnal cycle irrespective of fetch in winter in the UK.

The typical spatial scale for changes of the diurnal cycle apparently depends on many factors such as the area covered by sea breeze, the geometry of the coastal region, or the mutual orientation of the land and sea, and the direction of air flow. For the Baltic Sea conditions, this scale is of the order of the lower tens of kilometres. A study at Gotland suggests that within about 6 km from land to a marine site, there was no detectable change of the daily cycle [17] whereas it changes substantially across the Gulf of Finland [2]. Accordingly, the wind field at Pakri was estimated as moderately influenced by the mainland.

From the above analysis it might be concluded that the daily cycle of wind speed should be taken into account when a wind farm is planned in the vicinity of Pakri peninsula. A special investigation is needed to find out the distance where the daily cycle becomes negligible that is characteristic to open sea conditions [2] and to Hanko and Naissaar (not shown in this paper).

The frequency distribution of the wind speed (Fig. 5) varies to some extent during different seasons. This variation mostly follows the seasonal variation in

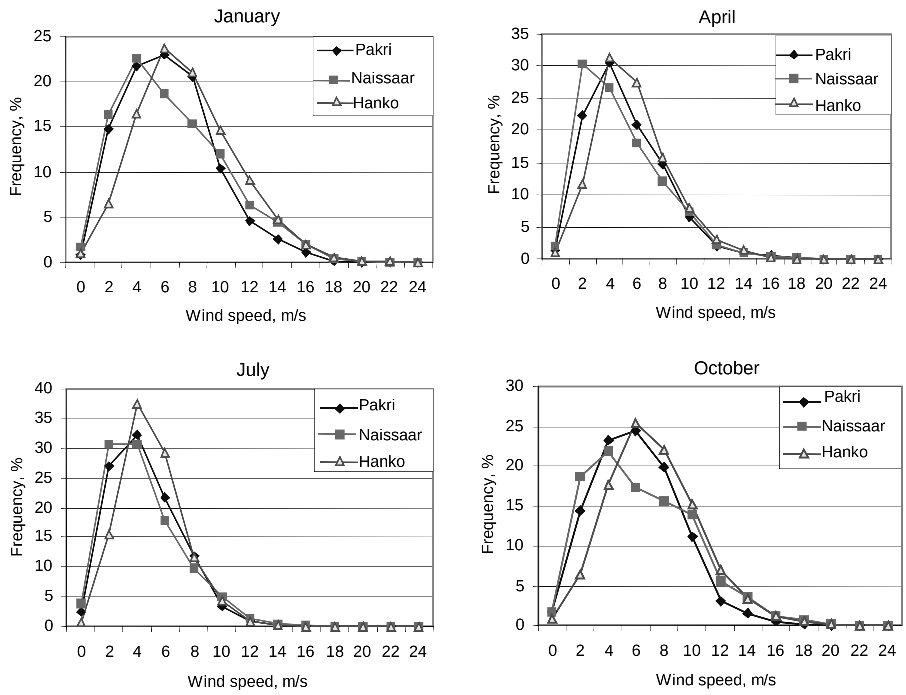

Fig. 5. Frequency of occurrence of different wind speeds during different seasons.

Table 1. Probabilities of some wind speed gradations for different measurement sites

	Wind speed <0.5 m/s, %			Wind speed >10 m/s, %		
	Pakri	Naissaar	Hanko	Pakri	Naissaar	Hanko
January	0.9	1.7	1.0	8.7	13.4	16.8
April	1.4	2.0	1.0	3.8	3.9	4.9
July	2.6	4.0	0.7	1.4	2.0	1.2
October	1.7	1.8	0.8	5.3	11.2	12.2

the mean wind speed (Fig. 3) whereas the shape of the relevant frequency distribution function remains basically the same. The variations also have a similar pattern at all three measurement sites. The largest deviations of the measured distributions from the classical Weibull distribution occur for Naissaar, apparently due to the asymmetry in the openness of the measurement field [12].

The frequency distribution functions shown in Fig. 5 enable one to estimate the probability of exceeding certain wind speed thresholds that could be important for wind farm planning. Table 1 shows that the probability of calm conditions (wind speed <0.5 m/s) at Pakri is comparable with that at the reference sites, but the probability of strong winds in autumn and winter is considerably lower. Thus, by planning offshore wind farms near Pakri, one should assume that high wind speeds occur more frequently compared to the wind statistics from the nearby coast.

4. DIRECTIONAL DISTRIBUTIONS

As mentioned above, coastal and mainland wind fields in the Baltic Sea region are more or less directionally homogeneous and only show a slight prevalence of west and south-west winds [7–9,15]. The directional distribution of larger wind speeds, however, is highly anisotropic [2,10]. These winds are mostly driven by large-scale atmospheric dynamics and are less affected by local orography and obstacles. As winds below 4 m/s have a minor importance in shaping the sea state and usually will not start wind generators, in the current study we only describe seasonal variations in the directional distributions of the winds with the speed over 5 m/s. This threshold is largely conventional and partially stems from the tradition of wind measurements in the former USSR where winds 0–5 m/s were treated as weak and winds 6–10 m/s as moderate.

Both the Pakri wind data and the reference data from Naissaar and Hanko show a clear seasonal variability in the directional distribution of moderate and strong winds (Fig. 6). The appearance of this variability suggests that the wind regime in autumn and winter differs from that in spring and summer. In October and January, the moderate and strong winds blow mostly from SW. There appears a secondary peak in the directional distributions in April and to a lesser extent July, reflecting a rather high frequency of NE (Pakri, Naissaar) or E

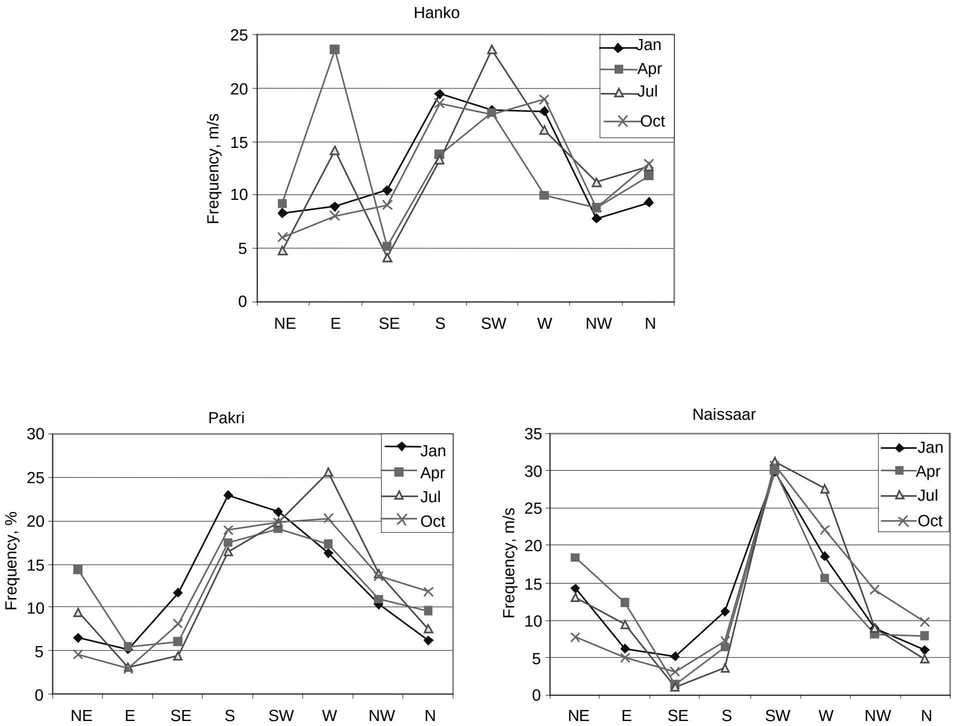

Fig. 6. Directional distribution of moderate and strong winds (wind speed >0.5 m/s) during different months at different sites.

(Hanko) winds. This peak occurs only in the Gulf of Finland and does not become evident in the Baltic Proper [2,10]. A certain difference of the directional location of the peak on the southern and northern coast most probably results from different positions of the sites with respect to the axis of the corresponding jet flow which evidently is mostly limited to the Gulf of Finland.

The low frequency of SE winds at Naissaar may be ascribed to the sheltering influence of the forest next to the measurement site [1]. The wind rose at Hanko shows that this feature is caused by atmospheric dynamics.

Wind farm planners are interested in frequency distributions of wind speed, blowing from different directions. We have separated sectors ±10° around the principal rhumbs and calculated the distributions for Pakri. Figure 7 shows that wind speed distributions during cold and warm half years are distinctly different for W and NW winds and slightly different for N, SW, S and SE winds. Wind speed exceeds the critical value of 4 m/s in more than 50% of cases during all seasons for W winds, in January, April and October for SW and S winds, in January and October for NW winds, in October for N winds and in January for NE winds.

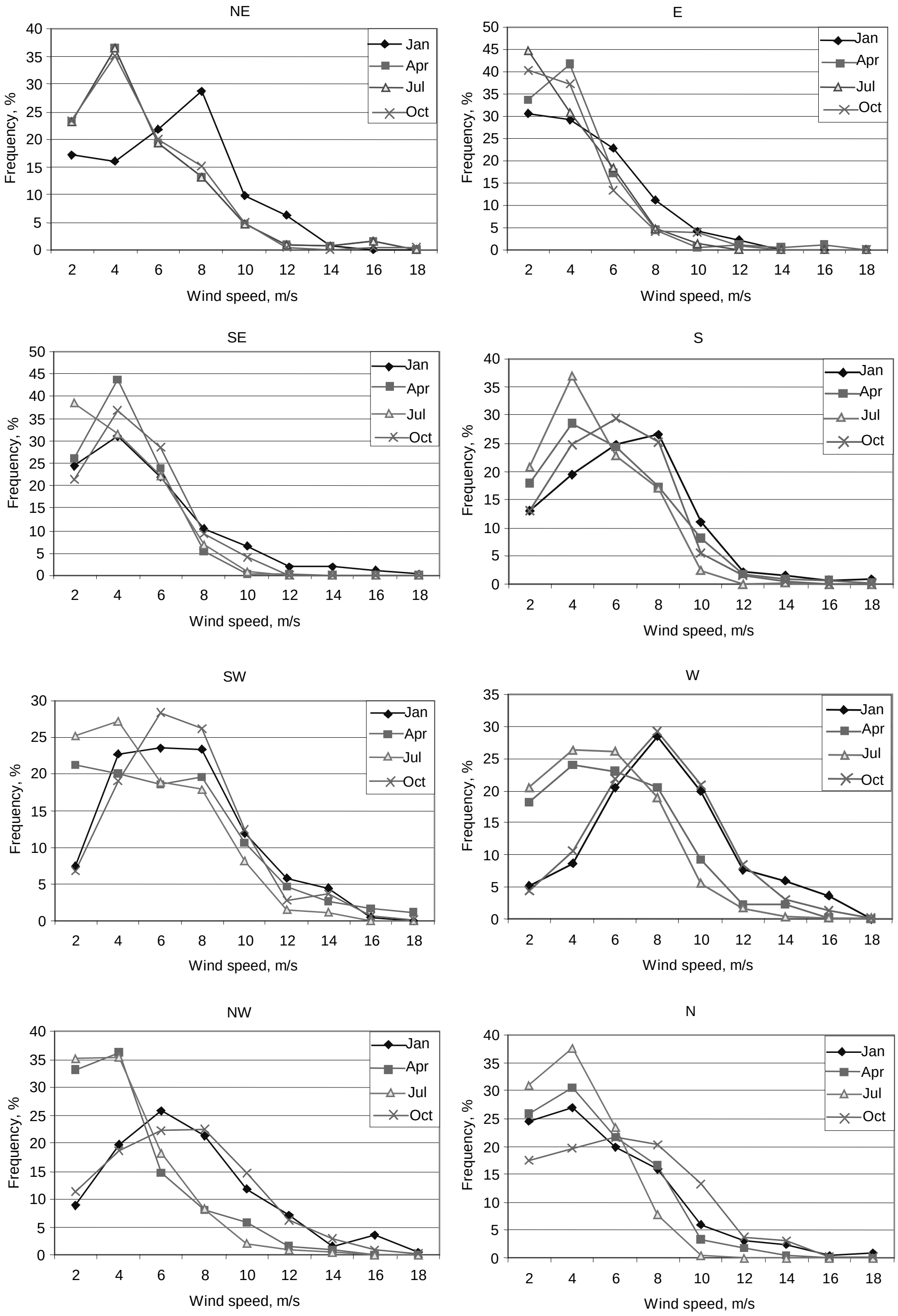

Fig. 7. Frequency of occurrence of different wind speeds during different seasons for different directions at Pakri.

5. CONCLUDING REMARKS

In an earlier investigation [2] it was shown that the directional wind distribution at Pakri and Hanko have wide maxima of SW winds and secondary maxima for relatively frequent ENE (E at Hanko) winds. This paper shows that such winds dominate only during the spring and summer seasons. It shows also that the low frequency of SE winds at Naissaar [1] is not only caused by the peculiarities of the observation site, but also by atmospheric dynamics, as a low minimum can be detected also in the directional distribution of Hanko (at least during the warm half year), although this observation site is open to SE.

The described strong diurnal cycle in the wind speed at Pakri with values deviating by ±0.75 m/s from the average may be a sign that the station does not represent offshore winds well [2]. This assertion is supported by the fact that Naissaar and Hanko both show negligible diurnal cycles. This feature may have major consequences in many areas of wind engineering. For example, before planning an offshore wind farm near Pakri, special observations should be undertaken to check if the daily cycle of wind speed is closer to Pakri measurements or to Naissaar and Hanko observations. A strong diurnal cycle in the average wind speed is a feature of vital importance for planning of coastal and offshore wind farms at sites with overall relatively low wind conditions. As most of the wind turbines on the market lose almost all their power for winds below 4 m/s, the potential diurnal variation of wind speed around this value may lead to the situation where turbines supply power only during a small period of the day. While this feature apparently does not reflect the factual properties of the marine wind field in cases when the main flow direction is onshore (like on the northern coast of the Gulf of Finland), it may extend quite a long way, at least some ten kilometres, offshore when the air flow has a mostly land fetch.

For the site in question, the relative importance of this peculiarity has the same magnitude as the seasonal variation of the average wind speed and thus is in no way negligible in planning of wind or coastal engineering activities. As this feature is the most pronounced for offshore winds, its influence in the coastal sea areas in the vicinity of Pakri may be relatively small in spring when a large part of moderate and strong winds blow from the east.

Directional analysis shows that the wind regime is different at all measurement sites for warm and cold seasons. At Pakri this difference is expressed best for NW and W directions. Here the best seasons for wind energetics are autumn and winter and the most favourable wind directions are S, SW, W and NW.

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Tuule omaduste sesoonne ja päevane muutlikkus Pakril

Sirje Keevallik ja Tarmo Soomere

On analüüsitud tuule omaduste pikaajalist, sesoonset ja päevast muutlikkust Eesti põhjarannikul Pakri meteojaama andmete (1969–1992) alusel. Aasta keskmise tuulekiiruse muutused on alla ±1 m/s pikaajalise keskmise (5,1 m/s) suhtes. Kuu keskmiste tuulekiiruste muutused aasta keskmise suhtes on ühesugused. Vaadeldud ajavahemikul ei muutunud tuule keskmine kiirus märkimisväärselt, kuid alates 1993. aastast vähenes see oluliselt vaatluskoha ümberpaigutamise tõttu. Tuulekiiruse sagedusjaotus muutub aasta jooksul, kusjuures suuremad erinevused ilmnevad lääne- ja loodetuulte puhul. Tuulekiiruse päevane muutlikkus on kuni ±0,75 m/s päeva keskmise suhtes kevadel ja suvel. Sügisel on päevane muutlikkus märksa väiksem ja talvel see praktiliselt puudub.