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Outlook for wind measurement at Estonian automatic weather stations

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Abstract. A preliminary analysis of the compatibility of wind properties obtained from continuous high-resolution recordings at automatic stations and traditional wind data (obtained by means of averaging the wind speed over a 10-minute interval and the wind direction over a 2-minute interval once in every 3 hours) has been carried out. Both wind speed data sets represent the same data population. The distribution of the differences between individual wind speed observations is non-Gaussian. The difference of estimates of the average wind speed is negligible for time scales of several weeks or longer. The shape parameter of the Weibull distribution for wind speeds is found to depend on the threshold for calm situations; it is close to 2 when wind speeds under 0.5 m/s are treated as calm. This choice also leads to a reasonable match of the corresponding wind roses.

Key words: wind speed, wind direction, wind measurements, automatic weather station.

1. INTRODUCTION

Like all other meteorological data, wind recordings have specific features that must be taken into account by the use and interpretation of them. It is well known that wind data characterize first of all the measurement site. They depend not only on the properties of the landscape but also on the particular location of the station in the landscape. For example, in Tallinn, there were two measurement sites not far away from each other. Ülemiste was situated on a high cliff, at 42 m above the sea level, and Kose below the cliff, at the altitude of 12 m. This difference caused systematically higher wind speeds (on average as large as approximately 1 m/s) at Ülemiste [1]. Such problems are generic in modelling of wind resources and special software, able to exclude the influence of nearby sheltering obstacles, roughness and orography of the surrounding is used by composing wind atlases [2,3]. Analogous, but more specific problems arise in attempts to restore winds on the open sea from the coastal data. Comparisons of on- and offshore data in some cases [4,5] (but not always [6]) enable us to get the relevant regression formulae.

The importance of local conditions becomes evident when the factually measured wind speed data are converted to the globally comparable values. According to WMO guidelines [7], a standard height of 10 m above open terrain is specified for the exposure of wind instruments. This combined requirement is difficult to meet because of the ambiguity of the definition “open terrain” and usually certain corrections are necessary to make the local wind data representative of a large area [7]. The differences in wind speed data, stemming from different measurement heights, can be minimized by using the boundary layer theory [8] or simply by assuming a logarithmic profile [9].

In the analysis of long meteorological time series and for reliable estimation of the wind climate or its trends, it is extremely important to have a homogeneous data set. The largest change in measurement facilities, methods, or regime in Estonia during the last decade is the (overall positive) introduction of automatic weather stations. While the older routine (in what follows called traditional) only provides the (observer-read) wind speed data once in three hours with a resolution of 1 m/s, the new devices are able to provide practically continuous data flow with an accuracy of 0.1 m/s. The new data offer completely new perspectives such as adequate separation of many local wind features (gustiness or short-time directional variability) from the large-scale wind patterns [10], exact quantification of duration and power of storm events, or adequate estimates of wind stability and power for wind energy purposes [11]. There is a temptation to use the new data for the characterization of climatological wind properties as an extension of the traditional data set. By doing so one must be careful, because the new data are partially obtained with the use of a completely different integration procedure and *a priori* it is not clear whether their statistical properties coincide with those of the traditional data [12]. Such problems may need attention already when the traditional 3-hour samples of the 10-minute wind speed are replaced by hourly samples [13]. Potential changes in the treatment of low wind speeds in the wind statistics not only distort the shape of the relevant Weibull distribution but also affect the estimates of extreme wind parameters [14].

This paper focuses on the analysis of the basic statistical properties of the contemporary and traditional wind data for selected observation sites in Estonia. Since the traditional data are not available any more, they have been simulated with the use of an integration procedure resembling the procedure used from the mid-1960s until the end of the century. We start with the description of the measurement routines, of the reasons of potential inhomogeneity of the wind data and of the data sets selected for the analysis. Then the coincidence of the basic statistical properties of the wind speed, obtained with the use of the two methods, is established. Further on, the deviation of the traditional wind data from the exact 3-hour, daily and monthly means is analysed. Finally, possibilities of the comparison of traditional and continuous wind direction data are discussed.

2. OBSERVATION TIMES, INSTRUMENTS AND AVERAGING SCHEMES

Instrumental wind measurements were started in Estonia in the first half of the previous century. Since then, several changes have taken place in the observation times (Table 1). Such changes may introduce appreciable differences into estimates of the diurnal cycle of wind parameters. For example, without observations at night, one cannot detect land breeze at coastal regions. Their absence may thus substantially influence the climatology of the wind directions. As the wind speed has minimum value at night, missing night observations are also reflected in higher values of the daily and monthly averages of the wind speed. Four years of parallel observations at Narva-Jõesuu, which were carried out three times (at 7, 13 and 21 Local Mean Time (LMT)) or four times (at 1, 7, 13 and 19 LMT) a day revealed the difference between the monthly mean values of the wind speed around 0.2 m/s [1].

In 1966, the frequency of observations was doubled and all previous observation times were shifted by one hour. The shift in time apparently did not cause any substantial changes in the statistics of the wind properties. The above-discussed example, however, suggests that extreme care must be exerted in the joint use of meteorological data that are recorded before and after 1966 in the climate analysis.

The measurements until the 1960s were carried out by means of the weather vanes. The mean wind speed and direction during a 2-minute interval were established visually. In the 1960s and 1970s, the weather vanes were gradually replaced by anemorhumbometers. An anemorhumbometer is a combination of an electrical cup anemometer (measuring the mean wind speed during a certain time interval) and a light vane, principally analogous to those used for determining the wind direction earlier. The most important difference is that the anemometer averages the wind speed over a 10-minute time interval. Differences in wind speed, recorded by these two instruments, were determined during a couple of years of parallel measurements. As could be expected from the difference in the

Table 1. Observation times

Period	Observation times								Time
Until 1940			07		13			21	Local Mean
1941	01		07		13		19		Local Mean
1942–1944			07		13			21	Local Mean
1945–1965	01		07		13		19		Local Mean
1966–	00	03	06	09	12	15	18	21	Greenwich Mean

averaging time, the anemometer frequently showed smaller values than the wind vane. For example, a daily average wind speed of 15 m/s, measured by an anemometer, was equal to a daily average of 17 m/s measured by a wind vane [15]. The averaging time of an estimate of the wind direction was not changed, but a dramatic increase of the resolution still introduces certain inhomogeneities of the data. Until the 1960s, the wind direction was registered by 8 or 16 rhumbs, that is, with a resolution of 45° or 22.5°. An anemorhumbometer gives the wind direction with a resolution of 10°. Fortunately, these inhomogeneities are easy to remove by means of minor calculations [16].

At the beginning of the 21st century, the Estonian meteorological observation network started to use automatic weather stations, as a rule MILOS 520 that are equipped with Väisälä wind instruments WAA151 and WAV151 [17,18]. They measure the wind speed and direction every second. Since the new cup anemometers still have a certain inertia, usually the instantaneous data are registered once in 10 seconds or used in the averaging schemes [17,18]. In Estonia, the average and extreme values are calculated and recorded over 2 minutes, 10 minutes, 1 hour and 3 hours.

The mean wind speed during a certain time interval (say, 3 hours), obtained from the continuous measurements via simple averaging, reflects its true value with a high accuracy whereas the traditional 10-minute mean (or their average for longer time intervals) can be interpreted as an approximation of the true value. Although the traditional wind speed recordings are not available in the stations, equipped with the new instruments, they can be easily simulated as average values of the wind speed during 10 minutes at the end of every 3-hour period [4,5]. Even though the average wind direction should be treated with care, for comparison purposes the traditional wind direction recordings are simulated as averages of continuously recorded wind directions over 2 minutes at the end of every 3-hour period (Table 2). The resulting data set (called quasi-traditional) uses only about 1% (of wind directions) or 6% (of wind speeds) of them.

The traditional wind measurement regime includes also recording the maximum (gust) wind speed during each 3-hour observation interval. An anemorhumbometer records this value during the last 3 hours [16]. As automatic weather stations also record the maximum wind speed during any prescribed time interval, there is practically no difference in gust recordings, provided the 3-hour time intervals coincide and the inertia of the cup systems does not differ substantially.

Table 2. Averaging schemes of wind data considered in the analysis

	Quasi-traditional recording	Continuous recording
Wind speed	10 minutes before the traditional observation time	3 hours between the traditional observation times
Wind direction	2 minutes before the traditional observation time	

Table 3. Wind speed data at the measurement sites

Station	Coordinates	Average, m/s		Standard deviation, m/s	
		Continuous	Quasitraditional	Continuous	Quasitraditional
Vilsandi	58°22′59″ N, 21°48′55″ E	5.71	5.73	3.07	3.18
Jõhvi	59°19′43″ N, 27°23′58″ E	3.5466	3.5470	1.96	2.05
Võru	57°50′46″ N, 27°01′10″ E	2.432	2.434	1.42	1.50

For the present analysis, data, recorded during 2004–2005 at three meteorological stations, were selected. The stations represent largely different climate regions and wind regimes. Vilsandi is the westernmost meteorological station situated on an island at the coast of the central part of the Baltic Proper (Table 3). The site is open to the dominating wind directions and the local wind climate represents well the marine wind properties [19]. The mean wind speed (5.7 m/s within the data in question, whereas its long-term mean apparently is well above 6 m/s [20]) is the highest of the three sites. Jõhvi is situated in a relatively flat terrain in North-East Estonia, not far from the Gulf of Finland. Yet this site is practically not affected by this relatively large water body, because the mean wind speed here is only about 3.5 m/s. Võru is located in South Estonia, the most continental region of the country. Wind regime in this area is additionally affected by a number of small hills nearby. The combination of the continental climate and the high roughness of the surrounding landscape probably are the basic reasons for the relatively low mean wind speed (about 2.4 m/s) at this site.

3. WIND SPEED

3.1. Basic statistics and long-term properties

The mean wind speed, calculated from the quasi-traditional and continuous data, perfectly coincides at Jõhvi and Võru, and insignificantly differs (by about 0.4%) at Vilsandi (Table 3). The differences in standard deviation of the wind speed are noticeable: about 6% at Võru, 4.5% at Jõhvi, and 3% at Vilsandi. Notice that the standard deviation here has the meaning of the deviation of the 3-hour wind speed (or its estimated value) from the long-term average wind speed, thus mostly reflects the variability of the physical process.

In many applications the basic wind properties can be assumed to be random functions of time and the traditional recordings to be their independent samples. These assumptions are usually adequate in cases when the time interval between subsequent observations is sufficiently long. This was evidently the case in Estonia when the wind properties were measured three or four times a day

(Table 1), because substantial correlation between wind properties is usually lost within 7–10 hours [11]. To a certain extent these assumptions are acceptable for the classical wind measurement scheme, consisting of 8 observations a day.

A fundamental question is whether the quasi-traditional and the continuous wind speed data represent the same data population. An unambiguous answer can be given for wind speed data whereas the relevant discussion for wind direction data is presented in Section 4. The wind speed data were first analysed with the use of the two-sample Kolmogorov–Smirnov test [21]. This test compares the distributions of values in two data vectors (optionally of different length), representing random samples from some underlying distribution(s). The null hypothesis is that the samples are drawn from the same continuous distribution. The test confirmed that the significance of the alternative hypothesis (that the data represent different continuous distributions) for the Vilsandi and Jõhvi data is less than 1%. For Võru data it is about 2%. The significance of the alternative hypothesis for the daily and monthly mean data was less than 0.01%. Therefore we can conclude that the quasi-traditional and the continuous wind speed data belong to the same data population. Moreover, the two populations of the monthly average data are practically undistinguishable with the use of statistical methods. This conclusion is further supported by the results of the the Wilcoxon rank sum test [22] (which is equivalent to the Mann–Whitney U test [22]) showing that all the complementary data sets have equal medians. Also the *t*-test shows that the sets in question have the same mean; however, since the data sets are not Gaussian, the outcome of the latter test should be interpreted as indicative. The described results suggest that, statistically, no major shift of the properties of the weather system occurs within the 3-hour sampling interval.

The distribution of wind speeds is usually approximated with the use of the two-parameter Weibull (Gnedenko) distribution [2,9,12,23]. It has the probability density function

$$f(u) = ku^{k-1}b^{-k}\exp[-(u/b)^k], \tag{1}$$

where $u > 0$ is the instantaneous wind speed, k is the shape parameter and b is the scale parameter, defined from the relationships

$$b\Gamma(1+1/k) = \overline{u}, \quad b^2\Gamma(1+2/k) = \overline{u^2}, \tag{2}$$

Γ is the gamma function and the overbar has the meaning of a sample mean. The value of $\overline{u^2}$ can be easily found from the definition of the classical (sample) variance

$$\sigma^2 = n\overline{(u-\overline{u})^2}\big/(n-1) = n(\overline{u^2}-\overline{u}^2)\big/(n-1), \tag{3}$$

provided the mean $\overline{u}$ and standard deviation σ of the wind speed and the number of wind samples n are given. For a long time series the latter relation is simply

$$\overline{u^2} = \sigma^2 + \bar{u}^2. \qquad (4)$$

In the North European climate, $k \cong 2.0,$ and the wind speed distribution is close to the Rayleigh distribution [2].

The existing data from Estonia, Finland [20,24] and the North Sea [25,26], among others, show that the wind speeds are mostly Rayleigh distributed in the marine wind climate. The shape parameter $k \cong 2.0 \pm 10\%$ at all the sites located at the northern coast of the Gulf of Finland that are open towards dominating wind directions [24]. At sites, such as Pakri and Kunda that are sheltered from marine winds by some local features, it differs for 17–23% from 2. To the knowledge of the authors, no analysis of the parameters of the Weibull distribution for other wind measurement sites in Estonia is available in international journals.

The statistical properties of the wind speed data for the sites, analysed in this paper, were checked with the use of the Jarque–Bera test and the Lilliefors test [27]. Since the wind speed is usually Weibull (or Rayleigh) distributed, it is not surprising that none of the data sets has Gaussian properties. The shape parameters of the Weibull distributions are quite close to 2 (Table 4). Their estimates, obtained from the quasi-traditional data, have a larger deviation from 2; however, the difference is a few per cent. The match $k = 2$ is nearly perfect for the continuously recorded wind data in which low winds (speed <0.5 m/s) are interpreted as calms. This finding suggests that the basic feature $k \cong 2.0$ of the North European wind climate may partially result from the limitations of the traditional measurement procedure, in particular, from its rounding routine.

3.2. Single observations

The difference of a single quasi-traditional measurement of wind speed within 10 minutes from the average of the continuous wind speed measurement over the relevant 3-hour period may be sometimes very large. This occurs mostly when the wind is blustery and the 10-minute wind speed is not representative of its true value within the whole 3-hour interval. The largest differences in the data set

Table 4. Parameters of the Weibull distribution

Station	Shape parameter *k*				Scale parameter *b*			
	Continuous		Quasi-traditional		Continuous		Quasi-traditional	
	All data	$u > 0.5$ m/s	All data	$u > 0.5$ m/s	All data	$u > 0.5$ m/s	All data	$u > 0.5$ m/s
Vilsandi	1.937	1.944	1.87	1.90	6.44	6.45	6.46	6.49
Vilsandi 1976–91 [20]			2.05				7.24	
Jõhvi	1.88	1.95	1.79	1.92	4.00	4.07	4.00	4.13
Võru	1.77	2.07	1.66	2.02	2.74	2.95	2.72	3.01

under consideration are found at Vilsandi: on November 29, 2004 at 15 GMT averaging over 10 minutes gives 1.1 m/s and averaging over 3 hours – 8.2 m/s. On June 8, 2004 the situation is just the opposite: the 10-minute average is 15.5 m/s and the 3-hour mean is 9.8 m/s.

Both the Jarque–Bera test and the Lilliefors test confirm that the distributions of the differences of the quasi-traditional wind speed data from the continuous ones are non-Gaussian at all sites. This feature is expressed by the relatively large deviations between the empirical probability density functions of the wind speed differences and the Gaussian ones with the same mean and standard deviation (Figs. 1 and 2). It is partially caused by a large amount of exactly coinciding measurements in the two wind speed data sets. In spite of this feature, a convenient measure of the difference of the 10-minute estimates from the true value is the standard deviation σ_s of its difference from the 3-hourly mean (Table 5). Although this measure also contains a certain portion of the natural wind variability, its primary meaning in the context of the current study is the typical error of the quasi-traditional measurements. For brevity, we shall speak below about the (standard) deviation of the quasi-traditional recordings, having in mind their deviation from the values, obtained from the continuous recordings.

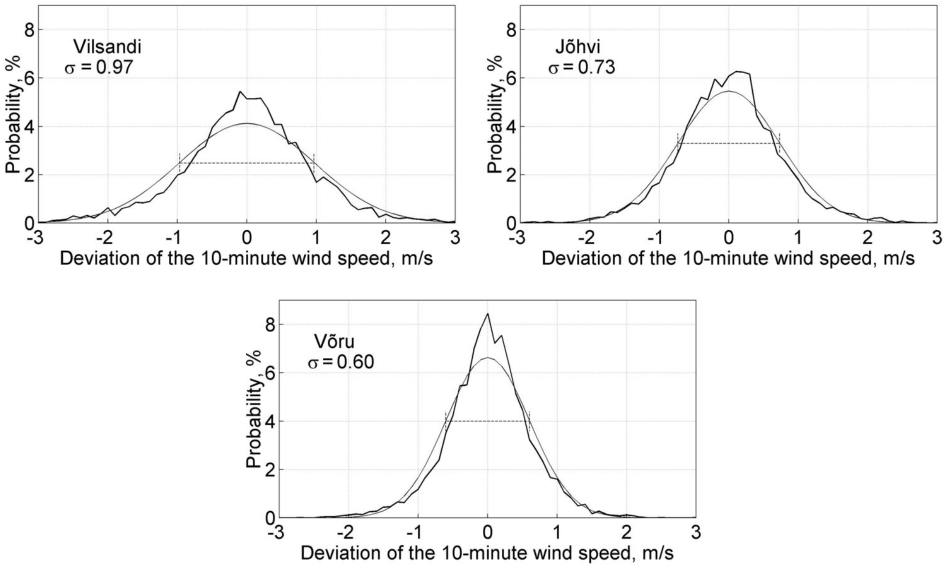

Fig. 1. Comparison of the distributions of differences of the quasi-traditional wind speed recordings from the 3-hour mean wind speed and the Gaussian distributions with the same standard deviations at three measurement sites for the resolution of 0.1 m/s.

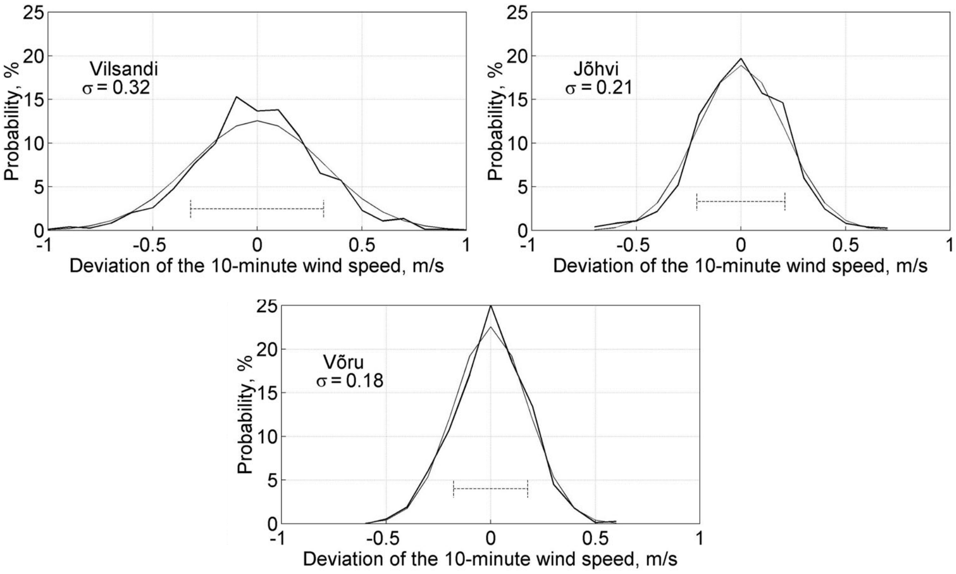

Fig. 2. Comparison of the distributions of deviations of the quasi-traditional daily average wind speeds from the true values and the Gaussian distributions with the same standard deviations at three measurement sites for the resolution of 0.1 m/s.

Table 5. Standard deviation of differences between quasi-traditional estimates of the wind speed and its true values, obtained from the continuous recordings

Station	Standard deviation (σ_s) of single measurements, m/s	Standard deviation (σ_d) of the estimates of the daily mean wind speed, m/s
Vilsandi	0.97	0.32
Jõhvi	0.73	0.21
Võru	0.60	0.18

The standard deviation for Vilsandi data $(\sigma_s \cong 1)$ is clearly bigger than that for the other two sites. Consequently, it is not unexpected that the largest deviations between the 10-minute and 3-hour estimates occur at Vilsandi. The Gaussian distributions with the same standard deviation (Fig. 1) underestimate the portion of fairly close wind speeds, somewhat overestimate the probability of occurrence of deviations, slightly exceeding the standard deviation, and fail to describe properly the largest deviations. For example, the maximum difference (7.1 m/s) at Vilsandi exceeds more than 7 times the standard deviation. If the deviations were Gaussian distributed, the probability of such a large difference would be of the order of 10^{-11}. For the number of data entries (about 5840) the deviations are not expected to substantially exceed the fourfold standard deviation, but for Vilsandi data this threshold is exceeded in 15 cases. Analogous feature becomes evident also in Jõhvi and Võru data where the largest differences are about $\pm 5.5\sigma_s$ and $\pm 5\sigma_s$, respectively.

3.3. Daily and monthly averages

The daily and monthly mean wind speed is obtained in both measurement schemes as an average of single measurements. Since each measurement of the continuous recording reflects very exactly the 3-hourly mean wind speed, their daily and monthly averages can also be interpreted as the true values. The quasi-traditional daily and monthly wind speeds represent 8 (for a day) or 224 to 248 (for a month) estimates (N) of the 3-hour mean wind speed, based on the 10-minute samples. The deviations of the quasi-traditional estimates of the daily mean wind speed from the true values are also more or less Gaussian distributed (Fig. 2). The standard deviations σ_d of the empirical distributions in Fig. 2 are much smaller than the analogous values σ_s for single measurements. This is an expected feature, because the quasi-traditional daily (monthly) mean wind speed can be interpreted, to a first approximation, as an average of several more or less independent estimates with roughly the same error distribution. The typical error (*resp* the standard deviation of the estimates) in such cases may be assumed to be roughly proportional to $\sqrt{N}$. The standard deviation σ_d of the quasi-traditional daily mean wind speed from the true value is thus expected to be about $\sqrt{8} \cong 3$ times smaller than the standard deviation of single measurements. The standard deviation σ_d (Table 5) is slightly smaller than the theoretical prediction; the reason apparently being the relatively small number of days (in total 731) under consideration.

The typical error of the quasi-traditional monthly mean wind values is evidently about from $\sqrt{224}$ to $\sqrt{248}$ (15 to 15.5) times smaller than the errors of single estimates, thus about a few cm/s for the sites in question. Consequently, even if there are certain minor deviations of the quasi-traditional daily mean wind speeds from the true values, the monthly mean values are expected to coincide practically with the results of continuous measurements within their resolution. This conclusion is indeed true for the data considered. The time scale, for which the typical deviation of the quasi-traditional average is expected to lie within the resolution of single measurements (0.1 m/s), is $N > 12.5\sigma_s^2$ days. It is about two weeks at Vilsandi and less than one week at Jõhvi or Võru.

The empirical distributions of deviations of single measurements and daily average wind speeds are more or less symmetrical: the positive and negative differences are fairly balanced for the selected thresholds (Table 6). An important non-Gaussian feature consists in the existence of several large differences between the quasi-traditional and continuous estimates of the daily mean wind speed. For the number of days in question (731) these differences generally should not exceed $\pm 3\sigma$. In extreme cases (Vilsandi, March 2, 2004) the traditional scheme overestimates the daily mean wind speed by 1.3 m/s, that is, about 4 times the standard deviation. Notice that the quasi-traditional scheme generally has larger overestimations than underestimations. This feature evidently reflects the asymmetrical nature of the Weibull distribution of wind speeds. Yet such an asymmetry becomes visible only for a small number of the largest deviations at

Table 6. Frequency of the occurrence of differences between quasi-traditional single measurements and daily wind speed estimates from the corresponding values obtained from continuous recordings

Deviation of the single quasi-traditional record from the continuous one				Deviation of the quasi-traditional estimate of the daily mean wind speed from the continuous one			
Deviation u', m/s	Frequency, %			Deviation u', m/s	Frequency, %		
	Jõhvi	Vilsandi	Võru		Jõhvi	Vilsandi	Võru
$u' > 2$	0.4	2.5	0.3	$u' > 0.4$	1.9	8.2	0.7
$1.1 \le u' \le 2$	6.4	8.8	4.1	$0.2 < u' \le 0.4$	14.2	14.6	11.5
$0.5 \le u' \le 1$	18.2	16.7	15	$0.1 < u' \le 0.2$	15.3	12.2	15.1
$-0.4 \le u' \le 0.4$	51.1	43.2	60.6	$-0.1 \le u' \le 0.1$	38.2	27.9	47.5
$-1 \le u' \le -0.5$	17.1	17.5	16	$-0.2 \le u' < -0.1$	16.4	13.1	12.3
$-2 \le u' \le -1.1$	6	9.4	3.9	$-0.4 \le u' < -0.2$	11.1	16.0	11.6
$u' < -2$	0.8	1.9	0.2	$u' < -0.4$	2.9	7.9	1.2

Vilsandi. For Jõhvi and Võru the maximum deviation of the daily wind speed is about $\pm 3.5\sigma$, which practically coincides with the estimates based on the relevant Gaussian distributions.

Thus the results of this and the preceding sections suggest that the distribution of deviations of quasi-traditional single measurements and estimates of the daily mean wind speed from their true values is generally symmetrical and resembles a Gaussian distribution for small and reasonable deviations. The proportion of exact quasi-traditional measurements is slightly larger than predicted by the Gaussian distribution, whereas the number of measurements with the typical error of the order of the standard deviation is slightly smaller. The distribution of the largest errors is also approximately Gaussian for the sites, representing continental wind climate. However, deflection of the distribution of the largest deviations from a Gaussian one is substantial at Vilsandi, where the overestimations by the quasi-traditional method are larger and occur more frequently than underestimations. This feature may reflect specific properties of marine winds.

Additional information about certain features of single wind speed estimates can be extracted from wind speed frequency distributions. For the following analysis, two months were chosen in stations that represent coastal (Vilsandi) and continental (Võru) wind regimes: November 2004 at Vilsandi (the largest monthly wind speed in the whole data set, Fig. 3) and July 2004 at Võru (the smallest monthly wind speed, Fig. 4). It can be noticed that averaging over 3 hours reduces the frequency of small wind speeds. This is the result of using the whole 180-minute period instead of a much shorter 10-minute averaging period and has been documented in a number of previous studies [28]. This feature implicitly shows that longer perfectly calm periods are infrequent both in marine and continental wind conditions in Estonia. It apparently contributes to the difference of the standard deviation of wind speeds, and also affects the parameters of the Weibull distributions (Section 3.1).

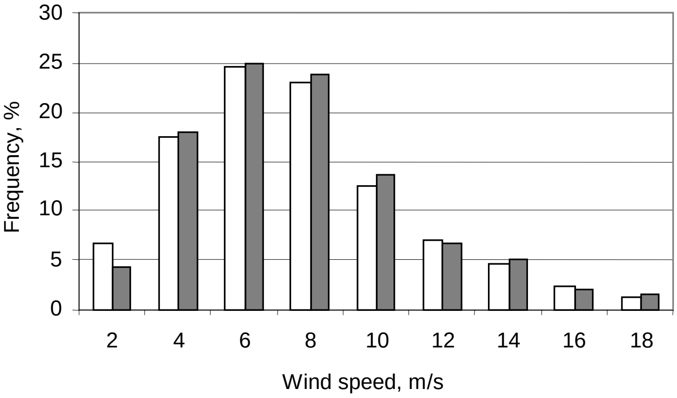

Fig. 3. Frequency distributions of the wind speed in November 2004 at Vilsandi: filled bars – continuous recording, empty bars – quasi-traditional recording.

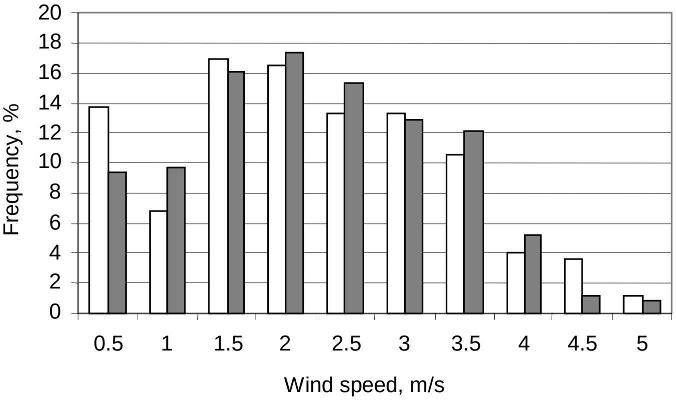

Fig. 4. Frequency distributions of the wind speed in July 2004 at Võru: filled bars – continuous recording, empty bars – quasi-traditional recording.

Figures 3 and 4 also show that the continuous wind measurement scheme seems to give a larger portion of higher wind speeds than the quasi-traditional scheme. This is an unexpected feature, because longer averaging times usually result in more narrow distributions of the frequency of different wind speeds [28]. Probable reason of this feature may be specific structure of local winds, statistical properties of which may differ from those obtained with the use of traditional 10-minute measurements as well as low wind conditions analysed in [10,12].

4. WIND DIRECTION

4.1. Single observations

Estimation of the wind direction using both vanes and anemorhumbometers may be formally interpreted as finding an average wind direction during the observation interval; yet their correct physical meaning consists in the determination of the most frequent wind direction during this interval. Heuristically it is obvious that in the majority of wind situations the wind direction does not vary substantially within a 2-minute interval. The fact that this assumption is not necessarily true even for 10-minute intervals is implicitly reflected in keeping the 2-minute interval for detecting the wind direction during the instrumentation and procedure changes in the 1960s. In principle, the average wind direction over longer time intervals is meaningless and even the 3-hour mean wind direction should be interpreted with a great care. Although the average direction is used in some serious studies (for example in [12] for relatively short time intervals), one is strongly advised to use the frequency of occurrence of winds from different directions (the wind rose).

This ambiguity becomes visible in the rather large scatter of estimates of the wind direction according to the two schemes (Table 7). Approximately in 1/3 of the cases the two schemes record wind directions that differ less than 6°. The typical difference between the estimates is about 10° and around 10% cases show differences over 40°. It may even happen that the estimates differ by 180°.

Such a large spreading is not unexpected and can be quantified with the use of certain simple qualitative concepts. The probability density function for wind directions is simply the classical wind rose (combined, if necessary, with the frequency of calm situations). If the wind rose were perfectly circular (that is, the probability of occurrence of winds from different directions is equal), the difference between wind directions at two independent measurement instants would be from 0° to 180° with an equal probability. Consequently, the mean deviation between any two recorded directions (a measure that has a clear meaning) is ±90°. In real wind conditions, certain wind directions prevail. The overall typical difference between wind directions of two independent measurements

Table 7. Frequency of differences between single measurements of the wind direction averaged over 3 hours and 2 minutes; since the true wind direction or the sign of the deviations have no meaning, only the magnitude of the difference is analysed

Difference	Frequency, %		
	Jõhvi	Vilsandi	Võru
<6 °	37	42	31
6°–15°	35	35	33
16°–40°	20	18	23
>40°	8	5	13

decreases as the anisotropy of the wind rose increases. For example, if winds at a certain site blow only from south-west or south, then the typical difference between two independent estimates of wind direction is 22.5°. Such a high anisotropy is not common and suggests that for independent wind measurements the typical difference in directions is of the order of 40°–50°. This estimate roughly coincides with observations in [12], where the standard deviation of wind directions from the formal average typically lies between 20° and 40°.

If wind directions during all the 2-minute intervals within any 3 hours were independent and the wind rose was more or less circular, only a few directions would match the direction, measured during the quasi-traditional session. Thus the basic consequence from Table 7 is that the difference between the quasi-traditional wind direction and the 3-hour mean is much smaller (about 10°) than it would be for independent measurements. The most probable reason is that the wind direction during relatively long time intervals (3 hours in the continuous recording scheme) is frequently concentrated in a narrow range. For Estonian coastal areas this feature – quite a strong correlation between wind properties within many hours – has been detected in [11] in relatively strong wind conditions. The above has shown that it apparently exists in a more continental wind climate as well. This is in line with the analysis in [10,12] that considers wind speeds less than 2 m/s, a range which includes a substantial part of winds in Võru. There is a negative loop in the autocorrelation functions for the horizontal wind, suggesting the existence of coherent structures in the near-surface layer on time-scales of 300–1200 s in low wind conditions [10,12]. A comparison of directions, obtained with different averaging schemes, thus may reveal important features of wind stability and duration at a particular site.

4.2. Monthly wind roses

The above analysis of the parameters of the Weibull distributions has shown that these distributions have a good match with the Rayleigh distribution when wind speeds under 0.5 m/s are treated as calm situations. Quite interestingly, the same threshold has an important role in the comparison of the wind roses for the two measurement schemes in question. Normally, the wind rose is drawn for 8, 16 or 36 rhumbs. In order to remove unnecessary details, we use the 8 rhumb system and show also the percentage of the calm situations defined here as the cases denoted by 0° in the data set. Actually, these cases involve also a certain amount of non-zero wind speed situations, because the instantaneous wind speed and direction are averaged and processed separately.

We use data from the same months that were used for Figs. 3 and 4. In November 2004, at Vilsandi the number of calm situations was negligible. Figure 5 shows that the continuous recording results in a more round wind rose than the quasi-traditional recording. In the light of the above this is an expected feature, complementary to the tendency of longer averaging times to shrink the distribution of wind speeds towards the most frequent wind speed [28].

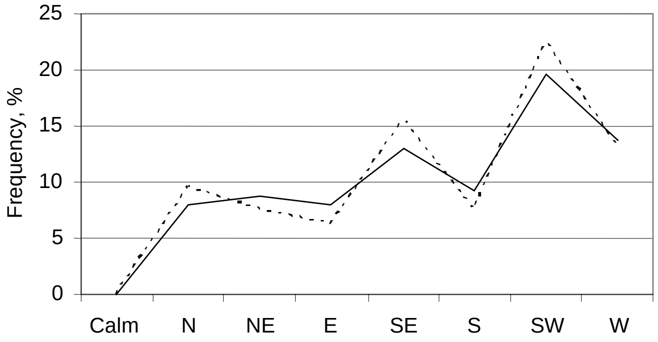

Fig. 5. Frequency distributions of the wind direction at Vilsandi in November 2004: solid line – continuous recording, dotted line – quasi-traditional recording.

Another major effect of the continuous recording scheme is the drastically reduced frequency of calm situations in comparison with the quasi-traditional averaging (Fig. 6). It is primarily evident in seasons with low wind speeds and at times it substantially distorts the shape of the wind rose. This reduction evidently reflects a certain ambiguity in the estimation of the frequency of calm situations from the automatic weather station data. Since the traditional anemorhumbometers record the average wind speed v with an accuracy of $\pm(0.5+0.03v)$ m/s [7,16], the situations where the 10-minute wind speed is less than 0.5 m/s are naturally interpreted as calms in the traditional routine. The automatic stations record the wind speed with a much higher precision (typically about 0.1 m/s), and many cases with a mean wind speed under 0.5 m/s are now interpreted as winds from a certain direction.

Consequently, the first step towards making the traditional and the new wind roses comparable consists of interpreting all cases when the wind speed is less than 0.5 m/s as calm situations. Comparison of Figs. 6 and 7 shows that doing so results in the correction of most of the deviations of the quasi-traditional wind roses from the ones obtained on the basis of continuous recordings.

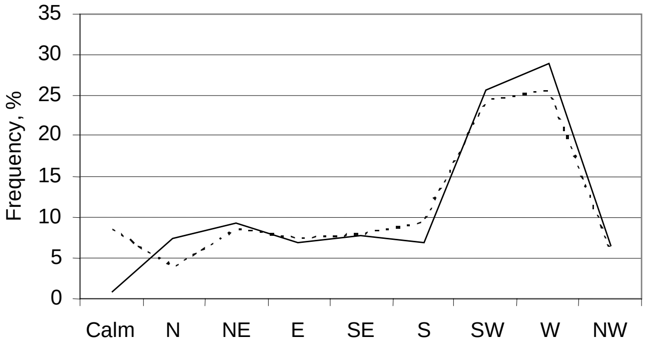

Fig. 6. Frequency distributions of the wind direction at Võru in July 2004: solid line – continuous recording, dotted line – quasi-traditional recording.

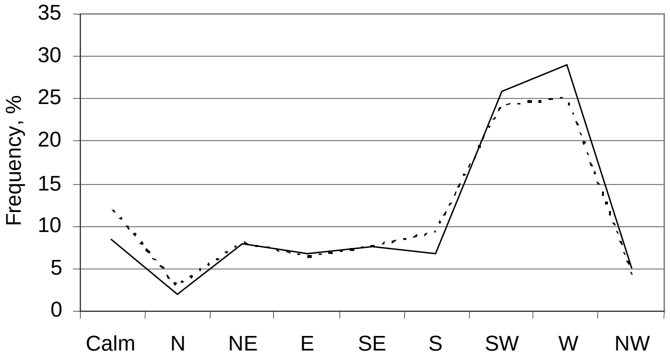

Fig. 7. Frequency distributions of the wind direction at Võru in July 2004 after additional analysis of calm situations: solid line – continuous recording, dotted line – quasi-traditional recording.

5. CONCLUSIONS

Continuous recording of meteorological data by automatic weather stations opens up new possibilities for the analysis of wind properties. Additionally to obvious simplifications in comparison of measured and numerically modelled wind data, it is now possible to separate certain specific features of the local winds from those excited by large-scale patterns. The performed analysis confirms the heuristically obvious guess that the traditional (that is, used since the 1960s) wind recording scheme describes satisfactorily the long-term (scales exceeding a few weeks) variability of wind speed. The distribution of the differences between the traditional and continuous wind speed data somewhat resemble the Gaussian distribution. Yet quite large deviations of a few quasi-traditional observations and daily averages of wind speed from the continuous recordings suggest that these differences may have certain site-specific features.

The analysis suggests that the potential influence of the dramatic increase of the accuracy of wind measurements on the wind statistics may have both site-specific and global dimension. A certain dependence of the parameters of the Weibull distribution of wind speeds on the threshold for calm situations is natural; however, it is probably not a simple coincidence that the shape parameter is close to two when the treatment of calm situations matches that in the traditional recording schemes with a resolution of 0.5 m/s. Although this feature has been only established for three selected sites, it suggests that one of the basic features of the North European wind climate – the approximately Rayleigh distributed wind speeds – may partially reflect the accuracy and resolution of the wind measurements in the past.

The consequences of the increased temporal resolution on the directional distribution of winds (the wind roses) are generally larger because of the ambiguity in obtaining the wind direction from longer recordings. Interestingly again, the distortions in the directional distribution remain reasonable when the direction recording routine simulates the traditional wind measurements, in which wind speeds under 0.5 m/s are treated as calms. Consequently, the first approximation in compiling long-term homogeneous data sets, containing both the traditional recordings and the results from automatic weather stations, consists in treating the situations when wind speed is less than 0.5 m/s as calms.

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Automaatjaamade väljavaated tuule mõõtmisel Eestis

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On võrreldud automaatjaamades pidevas režiimis mõõdetud kolme tunni tuule kiiruse ja suuna keskväärtusi 10 minuti keskmise tuule kiiruse ning 2 minuti keskmise tuule suuna väärtustega kolmes jaamas aastail 2004–2005 salvestatud andmete alusel. Erinevate meetoditega leitud tuule kiiruse andmestikel on sama tõenäosustiheduse jaotus. Andmete erinevuste jaotus erineb normaaljaotusest märgatavalt. Tuule keskmise kiiruse hinnangud erinevate andmestike baasil langevad praktiliselt kokku ajavahemike jaoks, mis on pikemad kui üks-kaks nädalat. Tuule kiiruste Weibulli jaotuse parameetrid sõltuvad tuulevaikuse defineerimise reeglitest. Weibulli jaotuse kuju parameeter on 2 siis, kui tuule kiirusi alla 0,5 m/s loetakse tuulevaikuseks; sel juhul on ka erinevate andmete alusel konstrueeritud tuuleroosid lähedase kujuga.