Proc. Estonian Acad. Sci. Eng., 2007, **13**, 1, 65–75

Periodicity of the average wind shear

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Received 5 Detsember 2005, in revised form 7 August 2006

Abstract. Higher level wind speeds are traditionally predicted either on the basis of the widely used logarithmic equation or using the Hellmann equation. In both equations, a coefficient that assesses the average wind shear curvature is usually used. This coefficient has been considered to be a constant, depending on the roughness of the surrounding landscape. In this paper, on the basis of wind speeds, recorded at different heights, we show that this coefficient is not a constant but it varies periodically with a period close to one year.

Key words: wind shear, periodicity, autocorrelation function.

1. INTRODUCTION

The energy yield of wind farms under design is evaluated on the basis of wind speed measurements, as a rule, at the height of 30–50 m despite the fact that the industrial height of typical modern wind turbine generators (WTG) is 70–80 m. To recalculate wind speed at a higher level, either a logarithmic equation or the Hellmann equation is widely used [1]. In both equations, a coefficient is used, which characterizes the average wind shear curve. This coefficient has been considered to be a constant for every roughness class of the surrounding landscape. The wind speeds, recorded at different heights at the Nässudden site (the Island of Gotland, Sweden), Harilaid Islet (The Moonsund Archipelago) and Tyrisalu Coast (both in Estonia) prove that this coefficient is not constant and it varies through the year. The same phenomenon has been observed at Avaste Hill (AVA), Kihnu (KHN) and Kunda (KND), where the recorded data series are too short for a reliable correlation analysis. These data are used below to illustrate the existence of the alternation of the average wind shear curvature. In this paper the observed phenomenon is studied, with an emphasis on its periodicity. Although the wind shear and its extrapolation have been studied in a number of papers [1–4], the periodical character of the average curvature was first reported in [5,6], without detailed analysis of the phenomenon.

2. DATA SERIES USED IN THE STUDY

To analyse a periodical process with the expected period about a year, data series recorded at different heights have to be long enough. An adequate data series is characterized in Table 1.

The NSD Land Tower is located in the south of the Gotland Island, on moderately variable landscape at a distance of about 1.5 km from the sea (which is located in the SSW direction). Harilaid Islet is located in the middle of Hari Sound (Estonian western archipelago). It is a lowland without bushes and trees and its distance from the nearest islands is about 7 km (large Hiiumaa Island in the south-western direction and a smaller Vormsi Island in the eastern direction). The Tyrisalu monitoring site is located in the north-west of Estonia, on the limestone bank (about 40 m above the sea level), and it has scarps on the western and northern directions. The bank is covered with bushes and ground rows. Data used for additional illustration are presented in Table 2.

The monitoring site on the Kihnu Island is the meteorological station at about 3 m above the sea level (asl), located between low juniper bushes and surrounded by the sea from three sides. Avaste Hill (20 m asl) is located about 40 km offshore, in an open landscape on a low hill (about 10 m over the surrounding fields). The monitoring site in Kunda (40 m asl) is located on an open gravel hill, covered by grass. It is located at about 3 km south from the coast.

Table 1. The “long” wind speed data series

Site	Abbre-viation	Coordinates		From	Until	Lower height, m	Upper height, m
		N	E				
Nässudden	NSD	~57°10′	~18°12′	Jan 1986	Dec 1989	10	32, 53
Harilaid Islet	HRL	58°56.4′	23°2.7′	Sep 1997	Dec 1998	20	50
Türisalu	TRS	59°25′	24°19′	Jan 2000	Dec 2004	20.5	40.5

Table 2. The “short” wind speed data series used for comparison

Site	Abbre-viation	Coordinates		From	Until	Lower height, m	Upper height, m
		N	E				
Kihnu Island	KND	58°06′	23°58′	May 1999	May 2001	10	27
Avaste Hill	AVA	58°37′	24°05′	Sep 2002	Sep 2003	10	27
Kunda	KND	59°30′	26°36′	Apr 2004	Up to now	9	27

3. OBJECT OF THE INVESTIGATION

The dependence of the average wind speed on the height is non-linear. Usually [2,7] the logarithmic equation has been used for the wind speed extrapolation:

$$u(H_2) = u(H_1)(\ln(H_2/H_0))/(\ln(H_1/H_0)), \tag{1}$$

where u is the wind speed, H_2 is the higher monitoring height, H_1 is the lower monitoring height and H_0 is the roughness characteristic. An empirical simplified equation, the Hellmann equation [1]

$$u(H_2) = u(H_1)(H_2/H_1)^{k_H}, \tag{2}$$

has also been often used; it gives practically the same result.

From Eq. (2) the Hellmann coefficient k_H can be calculated as

$$k_H = \log(u(H_2/u(H_1)))/\log(H_2/H_1). \tag{3}$$

The bigger the Hellmann coefficient, the bigger is the curvature of the wind shear.

4. TIME DEPENDENCE OF THE WIND SPEED AND OF THE CURVATURE OF WIND SHEAR

Data series from different heights with an hourly sampling interval were smoothed with a moving window along the data series with a step of two weeks. The window used for the analysis was mostly of three or six months long. Diagrams of the average wind speed, shown in Fig. 1, have a distinct periodical component, which is well known [6,8]. If a six-month averaging interval is used, the alternation of the wind shear curvature will decrease [5,6]. If the averaging window is infinitely long, we should find the ordinary value of the coefficient being constant.

The behaviour of k_H depends not only on the surrounding landscape, but also on the height of the measurement. Figure 2 demonstrates variation of the Hellmann coefficient k_H at the NSD site, which has a number of sensors at different heights (10, 32, 53, 75, 97, 118 and 140 m) [9]. Notation “@75/10” in Fig. 2 means that the coefficient has been calculated for the heights of 75 and 10 m and above. The horizontal axis in all time diagrams was built with a time step of two weeks and an averaging window of three months. Time has a relative value, i.e., the “zero point” is the beginning of each recording.

Figure 3 shows that the temporal variation (periodicity) of the wind shear curvature is an overall feature of (Estonian) wind climate. It is a proof that the discovered phenomenon exists probably everywhere in the natural environment

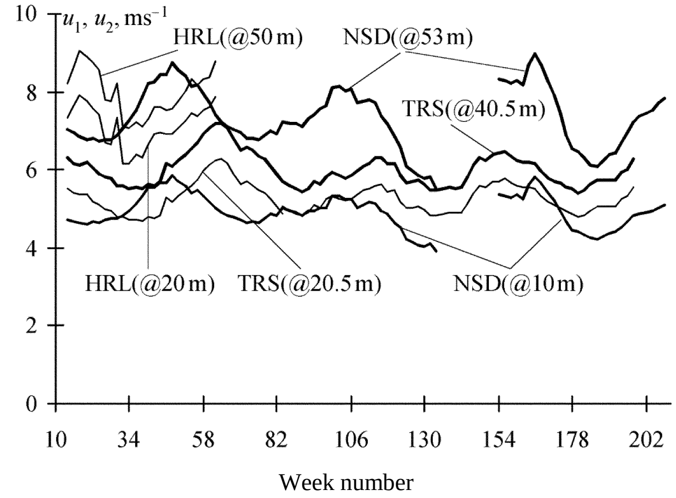

Fig. 1. Averaged (with the moving window of 3 months) wind speeds beginning from the start of each recording.

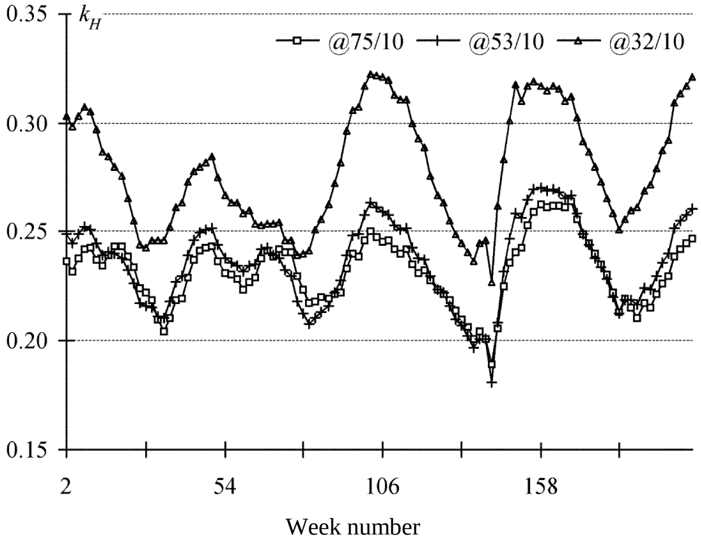

Fig. 2. Variation of the coefficient k_H with time for different heights of measurement at the NSD site.

and is hardly caused only by the influence of the sea. Monitoring site AVA is 40 km away from the coast and the variation of k_H there was the largest.

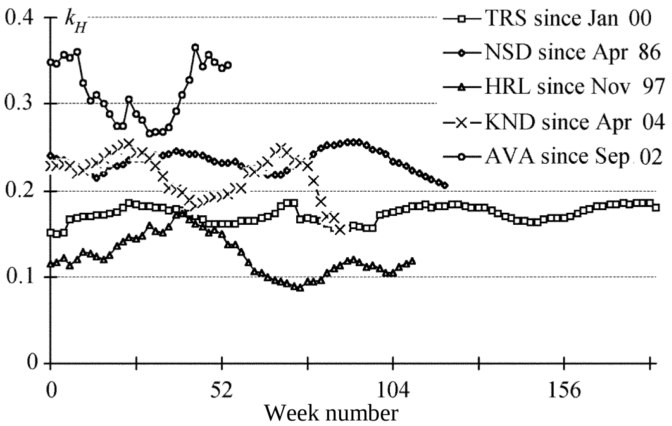

Fig. 3. Variation of the Hellmann coefficient at different monitoring sites.

5. CORRELATION OF THE WIND SHEAR CURVE WITH THE AVERAGE WIND SPEED

Since the diagrams in Figs. 1 and 2 are similar in nature, we can expect that the curvature of the wind shear may be correlated with the wind speed. This phenomenon is demonstrated in Fig. 4, where the correlation between the average wind speed and the average Hellmann coefficient is shown. At the majority of the sites, the correlation is negative, but at the NSD site it is positive for all the controlled heights 10/32, 10/53 (demonstrated in Fig. 4) and 10/75 meters. At the Harilaid site (not shown in Fig. 4), it is positive for the

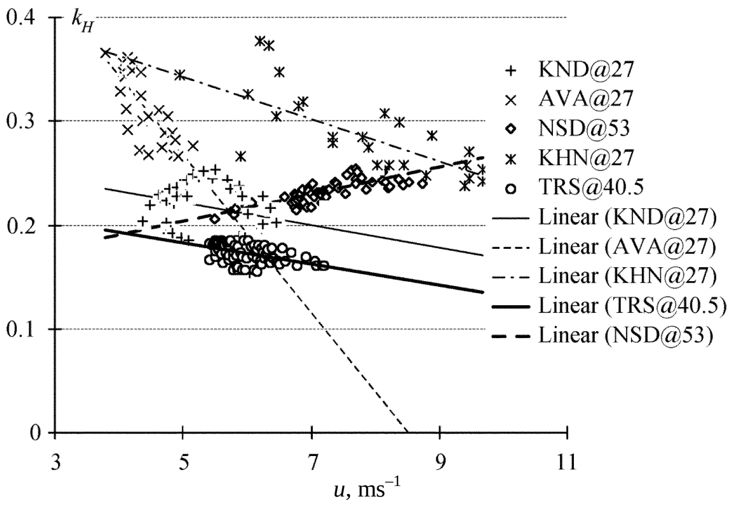

Fig. 4. Correlation between average wind speed u and the average Hellmann coefficient k_H.

heights 20/50 and negative for the heights 20/35. Thus, it appears that stronger winds are not only more stable [10], but also have a lower curvature. Although most of the monitoring sites (NSD, TRS, HRL, KND and KHN) are close to sea, the mentioned phenomenon is hardly caused only by the influence of the sea. Monitoring site AVA is 40 km away from the coast and the alternation of k_H there was the largest.

6. CORRELATION OF THE WIND SHEAR CURVE WITH THE AZIMUTH OF WIND

The exceptional behaviour of the wind shear at the NSD site is also confirmed by the directional dependence of the wind shear curvature, shown in Figs. 5–8. All of these figures use relative (to the corresponding maximum) values of the wind speed and of the curvature of the shear.

At the NSD site (Fig. 5) both u and k_H are almost independent of the azimuth of the wind shear and both maximums coincide. This can not be explained using the map only. All the other sites (TRS, AVA and KND) have a distinct directional dependence of k_H and the azimuths of the maximums of the wind speed and of k_H differ significantly. All of the four analysed sites show the maximum of k_H for east (E and EEN) winds and the maximum of wind speed for south winds (from SSE to SWW). The question of whether the periodicity of the wind direction influences the alternation of the wind shear curvature is to be studied.

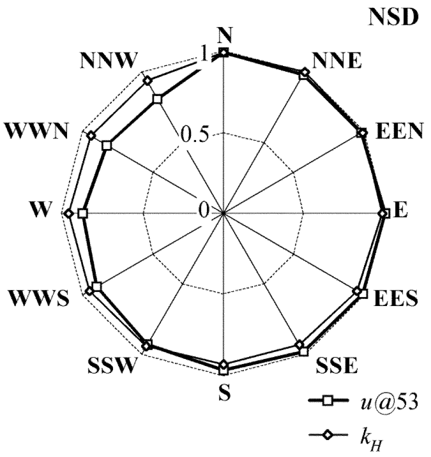

Fig. 5. Relative wind speed and relative curvature of the wind shear at the NSD site.

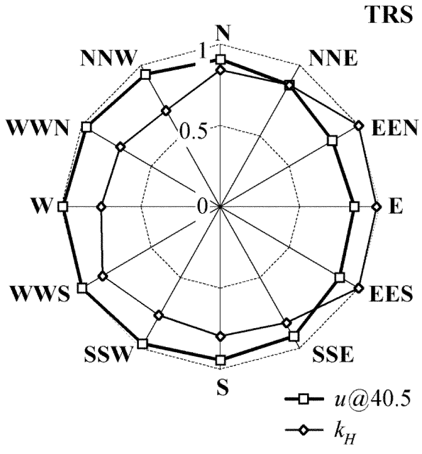

Fig. 6. Relative wind speed and relative curvature of the wind shear at the TRS site.

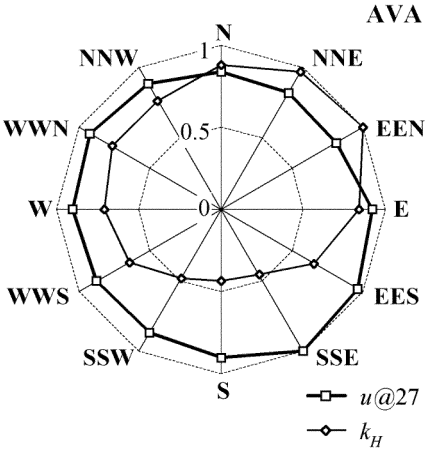

Fig. 7. Relative wind speed and relative curvature of the wind shear at the AVA site.

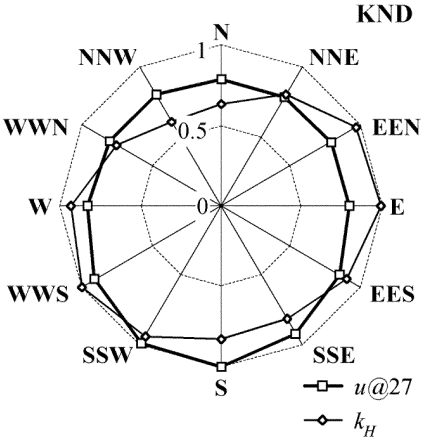

Fig. 8. Relative wind speed and relative curvature of the wind shear at the KND site.

7. REGULARITY OF WIND SHEAR ALTERNATIONS

The time diagrams of the Hellmann coefficient in Fig. 3 are presented only for illustration and are not sufficient to draw conclusions about its periodicity. To provide accurate data for the time series of k_H, the autocorrelation functions were created (Fig. 9). This figure shows that the periodicity of the wind shear curvature (the alternating Hellmann coefficient) is significantly greater than its random component.

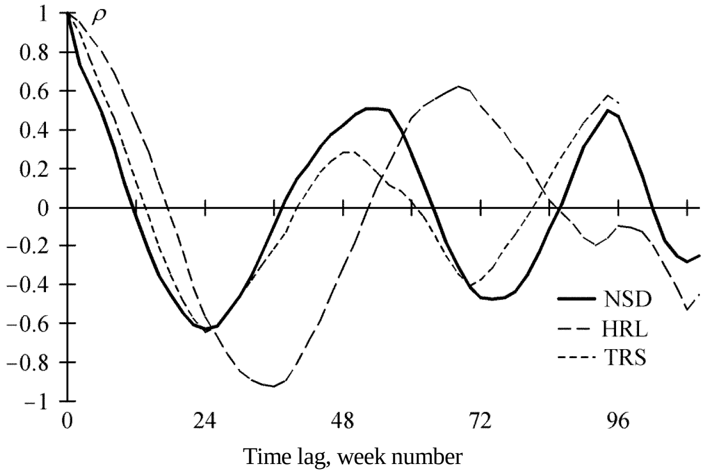

Fig. 9. Autocorrelation functions (ρ) of the alternation of the Hellmann coefficient k_H.

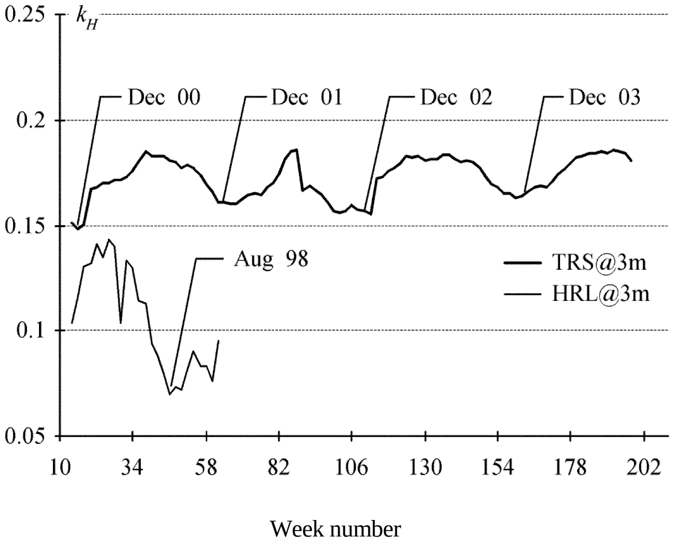

Fig. 10. Time dependence of the Hellmann coefficient at the HRL and TRS sites for the averaging window of 3 months.

For the NSD and TRS sites, the periods are equal and close to a year. For the HRL site, the period is different (close to 18 months), but this period is distorted by a too short time series (the same 18 months). Probably the real period for the HRL site is also about a year. Autocorrelation functions do not show the phases of the periodical processes and we have to return to the time diagram in Fig. 10, where we observe a contradiction: the maximums and minimums at different sites do not coincide in different seasons.

8. EVALUATION OF THE INFLUENCE OF THE ALTERNATING WIND SHEAR ON THE GENERATED ENERGY

First, we shall make a rough evaluation. More exact analysis is justified if the first step shows a significant influence of the alternating wind shear on the energy generation. For rough evaluation, we shall use the stepwise approximation of the alternating coefficient k_H (Fig. 11). We shall choose a year-long interval, which consists of a higher and a lower "half-sine" around the average value for the full year $k_{H,\text{aver}}$. During a half year, the "half-sine" function is approximated by the constant value ($k_{H,\max}$ and $k_{H,\min}$, respectively), equal to the average of the Hellmann coefficient during this time interval. We use the corresponding average values of wind speed at the lower level and we recalculate the wind speed at the upper level of 80 m. In the calculations of the energy yield P^*, we have to consider the non-linear load characteristic of the WTG in the active range of performance $3.75 < u < 11.99$ m s^{-1}:

$$P^{*} = \frac{1}{47}(u - 3.75)^{1.75}. \tag{4}$$

As Eq. (4) describes the power curve in relative units, the result – energy yield for a year – can be found in relative units of kWh per kW. Even if $|k_{H,\max}| = |k_{H,\min}|$, the generated energy during both half-years will not be equal due to the non-linearity of (4). That we can prove by finding the derivate of Eq. (4):

$$\mathrm{d}P^{*}/\mathrm{d}u = (1.75(u - 3.75)^{0.75})/47. \tag{5}$$

The finite power deflections will be

$$\varDelta P^{*} = 0.0372\,(u - 3.75)^{0.75}\,\varDelta u. \tag{6}$$

It means that the (recalculated) wind capacity at the upper level depends on the drift of the wind speed due to the variation of the Hellmann coefficient.

The example in Table 3 uses the data of the NSD and TRS sites. For each site, the columns have the following meaning:

- “w N#” is the analysed time interval (weeks);
- $u(\ldots)$ is the average wind speed in this time interval corresponding to the height, shown in the brackets;
- $k_H \in \{k_{H,\max}, k_{H,\min}\}$ is the averaged Hellmann coefficient, valid for the considered time interval;
- E^{*} is the produced relative energy.

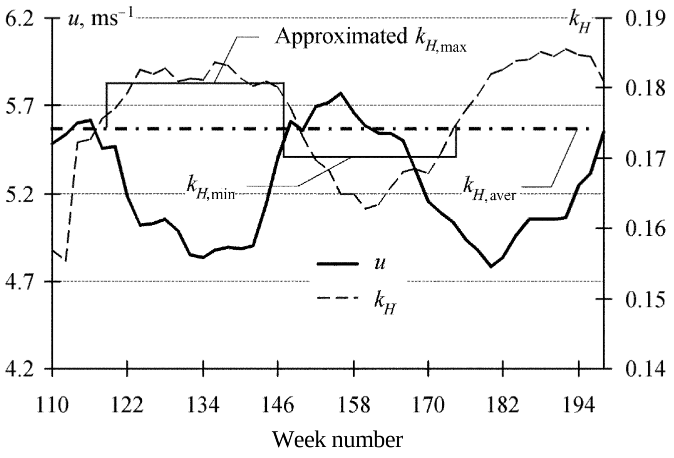

Fig. 11. Example: stepwise approximation of the Hellmann coefficient at the TRS site.

Table 3. Calculated relative energy yield per year

	TRS					NSD				
	w N#	$u(20.5)$	k_H	$u(80)$	E^*, kWh/kW	w N#	$u(10)$	k_H	$u(80)$	E^*, kWh/kW
$@k_{H,\max}$	118–144	5.04	0.181	6.45	703.8	36–62	5.47	0.240	9.00	2260.1
$@k_{H,\min}$	145–170	5.54	0.169	6.98	962	63–88	4.81	0.226	7.69	1365.2
Total					**1665.9**					**3625.2**
$@k_{H,\text{aver}}$	118–170	5.28	0.175	6.71	**1652.1**	36–88	5.14	0.233	8.35	**3581.1**

In Table 3, symbol $@k_{H,\max}$ denotes the calculated energy for the higher value of the Hellmann coefficient; symbol $@k_{H,\min}$ denotes the calculated energy for the lower value of the Hellmann coefficient and $@k_{H,\text{aver}}$ denotes the calculated energy by the traditional approach. Bold numbers in the table are the calculated energy yield.

This example shows that the influence of the alternation of the Hellmann coefficient has an order of 1% and it is on the level of errors of the prediction of the energy yield. No exact analysis is needed. If the monitoring interval is six months (that is practiced sometimes), the error of prognosis may be significantly greater and it depends on the phase of the alternation of k_H.

9. CONCLUSIONS

1. The presented results suggest that the temporal variation (periodical component) of the wind shear curvature is an overall feature in Estonian wind climate.
2. The period of variation of the Hellmann coefficient (alternating of the curvature of the wind shear) is close to one year.
3. The required monitoring interval for an energy prognosis should be one, two, three etc. full years.
4. No single reason of the alternation of the wind shear curvature was established. Most probably it is caused by a complex of physical processes, like changes in the wind speed and direction, and also by the surrounding landscape.
5. If the conducted wind monitoring is of the recommended length, the influence of the alternating curvature of the wind shear on the produced energy is low and practically insignificant.

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Tuule kiiruse keskmise vertikaalepüüri perioodilisus

Teolan Tomson ja Hannu Lamp

Tuule kiirust mõõdetakse energeetilistel eesmärkidel enamasti 30–45 m kõrgusel ja elektrituuliku eeldataval võlli kõrgusel (tänapäeval 70–100 m) leitakse tuule kiirus arvutuslikult. Ümberarvutuse aluseks on kas teoreetiline logaritmiline arvutusvalem või empiiriline Hellmanni võrrand. Mõlemal juhul on vaja teada tuule kiiruse keskmise vertikaalepüüri vertikaalset muutumist määravat tegurit, mis leitakse kahel erineval kõrgusel tehtud mõõtmistest. Seda tegurit käsitatakse traditsiooniliselt konstandina, mis on korrektne, kui keskmised tuule kiirused on leitud lõpmatult pikast mõõtmiste reast. Kui määrata tuule keskmist kiirust lõpliku ajaintervalli (mõni kuu) jaoks, siis selgub, et see tegur ei ole konstantne ja näib omavat aastasele lähedase perioodiga komponenti.