Wind variability in the High Tatras Mountain

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A b s t r a c t : Measurements and registration of the wind speed and wind direction are systematically carried out at the meteorological observatories Skalnaté Pleso and Stará Lesná, located in the High Tatras. Based on these measurements the seasonal variability of the wind speed and wind direction in the High Tatras region is studied. The different altitude, as well as the distinguished topographical conditions at both observatories enable to study the temporal variability of air circulation at two different altitudes. Anemographic records of the mean hourly wind speed and wind direction covering the period of the years 1992-2006 were used as an experimental basis. The methods of mathematical statistics were applied to the evaluation of these time series.

Key words: anemographic record, wind speed, wind direction, daily and seasonal courses, statistics

1. Introduction

Wind is the most variable meteorological element, namely in the atmospheric boundary layer. Its local and weather variability depends upon the area contour, and therefore the topographically highly complex terrain of the High Tatras creates various conditions for the surface air circulation. This complexity of topographic conditions in the High Tatras finds its expression also in considerable diversity of wind conditions. Therefore, it is required to use an adequate observation of wind direction and wind speed to obtain the analysis of wind in the High Tatras.

Wind conditions in different high-mountain localities in the High Tatras have been evaluated. On the basis of wind speed and wind direction measurements 3 times a day at 7, 14, and 21 h of the local time, numerous works were published, as it follows from bibliography "Climate of Tatras"

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(*Otruba and Wisniewski, 1974*). In some works, there were also evaluated results of analysis of daily course of wind speed on the basis of evaluation of anemographs (*Otruba, 1987; Ostrožlík, 1991; Otruba et al., 1988*). However, the most detailed analysis and interpretation of the field of wind speed in the High Tatras region, which is based on surface measurements, is provided by Otruba and Wiszniewski in the mentioned monograph.

2. Material and methods

Measurements and recording of wind speed and wind direction at Skalnaté Pleso ($\varphi = 49°12'$N, $\lambda = 20°14'$E, h = 1778 m a.s.l.) and Stará Lesná ($\varphi = 49°09'$N, $\lambda = 20°17'$E, h = 810 m a.s.l.) are carried out by central measurement data system ESM 200. The 10 minute scanning interval of the local time is used for sensor. These instantaneous data are stored in the centre measurement station. The hourly averages, each calculated from 6 instantaneous values, are loaded on magnetic medium. As a foundation the hourly data of anemographic measurements of wind speed and wind direction during the 1992-2006 period were used.

The methods of mathematical statistics (*Anděl, 1985; Kendall and Stuart, 1968; Nosek, 1972*) as well as harmonic analysis (*Brooks and Carruthers, 1953; Conrad and Pollak, 1962*) were applied to the evaluation of these time series.

3. Results and discussion

Based on numerical and graphical analysis of 15 year time series of hourly anemographic data of wind speed and wind direction at Skalnaté Pleso and Stará Lesná some quantitative characteristics and peculiarities of daily and annual courses in different topographic localities are evaluated and interpreted.

The total windiness of a position may be expressed most simply by the total average wind speed regardless of direction and including calm.

Many statistical characteristics of wind speed: average, median, extreme values, standard deviation, coefficient of variation, etc. are introduced in

Table 1. Processing the extensive material showed that in spite of the fact that the occurrence of calm is more frequent at Skalnaté Pleso (3.5%) than at Stará Lesná (0.4 %) (in annual mean), the slope position of Skalnaté Pleso is windier (3.3 m s^{-1}) in comparison with mountain foot of Stará Lesná (2.1 m s^{-1}). Older data from Skalnaté Pleso show (*Otruba and Wisniewski, 1974*) the mean value of wind speed at Skalnaté Pleso during the period 1941-1950 and 1951-1960 (3.7 m s^{-1}, 3.8 m s^{-1}, eventually) was a little higher than during the investigated period.

The distribution on wind direction is determined particularly by topographical conditions, nearby and more distant surroundings of the investigated locality. Therefore, each position or area has in a multiannual mean its own characteristic distribution of wind directions. Its total picture does not change even under the influence of the long-term wind fluctuations. Annual fluctuations of the general circulation are reflected in a relative increase or decrease of corresponding wind directions in the corresponding parts of the year. Hence, the field of air flow in the surface atmospheric layer, generated by general atmospheric circulation, is extremely influenced by terrain

Table 1. Statistical characteristics of the mean annual values of wind speed at Skalnaté Pleso and at Stará Lesná during the 1992-2006 period

Variable	Wind speed in m s^{-1}	
	Skalnaté Pleso	Stará Lesná
Sample size	15	15
Average	3.34	2.12
Median	3.30	2.06
Mode	3.20	1.96
Geometric mean	3.33	2.10
Variance	0.07152	0.07932
Standard deviation	0.26744	0.28163
Standard error	0.06905	0.07272
Minimum	3.01	1.69
Maximum	4.02	2.64
Range	1.01	0.95
Lower quartile	3.13067	1.88283
Upper quartile	3.49475	2.39717
Interquartile range	0.36408	0.51433
Skewness	1.25161	0.21436
Kurtosis	1.81613	-0.73661
Coeff. of variation	7.99672	13.31415

morphology (*Otruba, 1964*).

High-mountain massif of High Tatras has a great part on wind field deformation. The mentioned massif represents a topographical barrier, especially for the northern components of general atmospheric circulation. It also demonstrates the percentage distribution of the surface wind directions in Fig. 1. According to the data in Fig. 1, it can be seen that Skalnaté Pleso is characterized by prevailing south-western air flow components (mainly WSW and SW). On the opposite, the north-western components of wind are at least probable. At Stará Lesná the most frequent winds are with the south components of air flow (mainly S and SSW), while the north-eastern winds are the rarest. The seasonal fluctuation of circulation, taken as an annual mean, is biased, and the distribution of wind directions during the year gives a summary picture only of the distribution of winds appearing during the year.

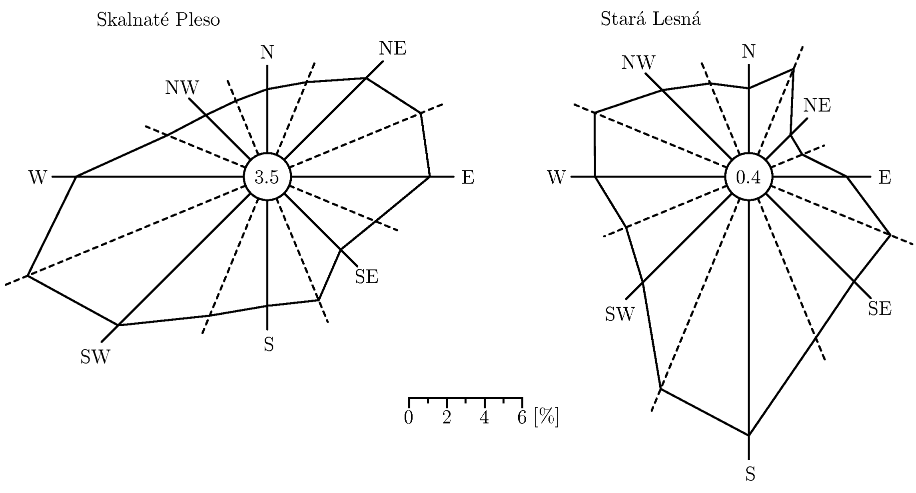

Fig. 1. Wind direction roses at Skalnaté Pleso and Stará Lesná during the 1992-2006 period. In the centre of the rose is percentage data of calm.

The annual course of particular wind directions does not depend only on the annual fluctuation of the general circulation, but also on the terrain wind swerving and on the occurrence of local thermic winds. In mountainous areas of the territory it has often been observed that the annual course of some wind directions has been caused by the annual course of local winds blowing in definite directions and not by the fluctuation of directions within the general circulation of air over our territory (*Otruba, 1964*).

A comparison of occurrence frequency of the two most frequent winds - WSW at Skalnaté Pleso and S at Stará Lesná (Fig. 2) shows that these selected types of wind direction have no distinct annual course.

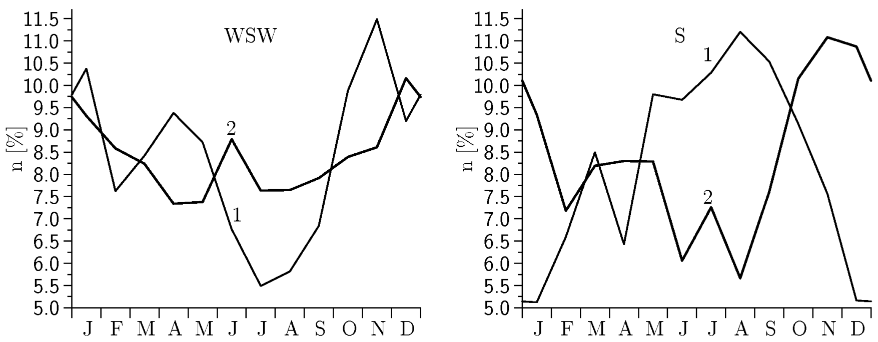

Fig. 2. Annual course of the relative frequency n in % of WSW and S wind directions at Skalnaté Pleso (1) and at Stará Lesná (2) during the 1992-2006 period.

On the other hand, the daily course of both the most frequent winds has characteristic and expressive behaviour with one maximum and one minimum (Fig. 3). It is interesting, while in the case of WSW wind directions the minimum is around the midday, at this time of the day the S wind directions have a maximum.

Wind speed in various wind directions is clearly illustrated in Fig. 4. An analysis of mean speed of wind directions according to wind roses gives a more detailed picture of a dissimilar intensity of flow of individual wind directions in various directions. Based on the vector sizes we can take measure of the qualitative and partly quantitative dynamic conditions of general air circulation, as well as wind speed changes due to the mountain barrier. From the values of vectors, it can be seen which directions participate to what extent on the whole wind roses in the slope position at Skalnaté Pleso, as well as in the foothills at Stará Lesná. For example, it can be seen that the most numerous wind directions at Skalnaté Pleso (WSW and SW) have also the greatest wind speeds. Similar situation is at Stará Lesná, but here

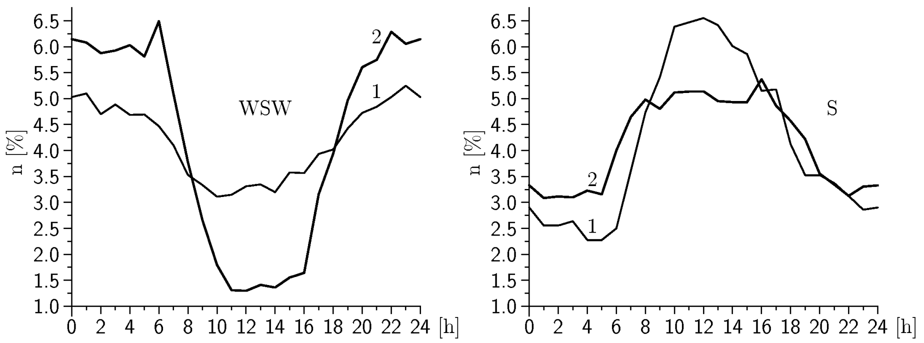

Fig. 3. Daily course of the relative frequency n in % of WSW and S wind directions at Skalnaté Pleso (1) and at Stará Lesná (2) during the 1992-2006 period.

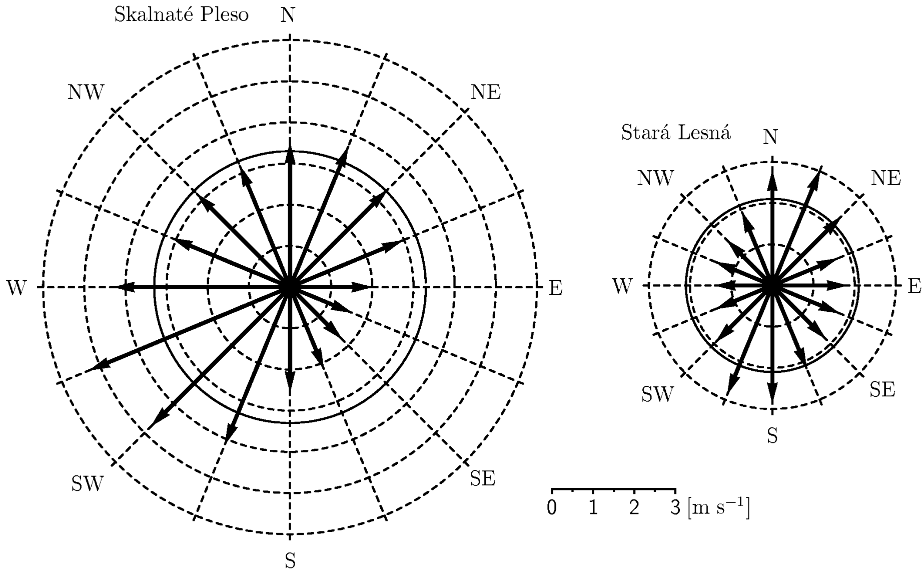

Fig. 4. Roses of mean speed of wind directions at Skalnaté Pleso and Stará Lesná during the 1992-2006 period. Mean value of wind speed of the investigated period is depicted by the solid circle.

it can be seen that the greatest wind speeds are along the ENE-SSW axis. Besides the minimum mean wind speed at Skalnaté Pleso during the winds with the south-eastern wind components (from E to S), being at Stará Lesná the minimum wind speed falls to the directions with the western wind components (from WNW to NW).

Mean hourly values of wind speed during the year – experimental and theoretical (the first and the first two harmonic components) – are graphically presented in Fig. 5, to characterize the annual course of the total windiness at Skalnaté Pleso and Stará Lesná. Harmonic analysis was used in these calculations (*Brooks and Carruthers, 1953; Conrad and Pollak, 1962*). The course of the curves in Fig. 5 indicates that at both localities the annual course of the wind speed is not so simple. For example, there are two maxima during the year – in spring and in autumn. But the mean course can be absolutely different in individual years of the investigated period.

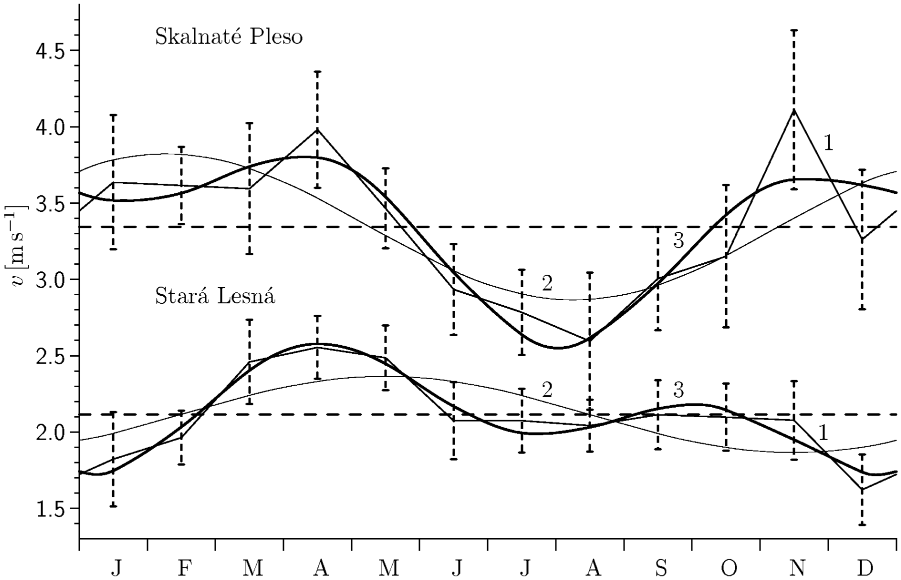

Fig. 5. Annual course of wind speed v in m s^{-1} at Skalnaté Pleso (1) and Stará Lesná (1), and its first (2) and the first two (3) harmonic components during the 1992-2006 period. Error bars represent variance and indicate variability within the month.

Using experimental data periodic annual course of wind speed v in m s^{-1} at Skalnaté Pleso and Stará Lesná can be expressed by the first two harmonic components in the form

$$v = 3.444 + 0.478 \sin(x + 66°51') + 0.300 \sin(2x + 242°27') \ldots\ldots\ldots \text{Sk. Pleso}$$

and

$$v = 2.115 + 0.249 \sin(x + 330°11') + 0.250 \sin(2x + 280°36') \ldots\ldots \text{St. Lesná}$$

where x is a time angle. It is computed from $x = iz$, $z = 360°/P$, $i = 0, 1, 2, \ldots \text{n} - 1$, if P denotes the length of the period investigated. For example, in our case n = 12, $P = 12$ months and $z = 360°/12 = 30°$.

From the first comparison of the curves in Fig. 5 – experimental and calculated - we can see that in the case of annual course of wind speed the fitted curves of the first two harmonic components give a good agreement between the observed and calculated values.

As it has been mentioned the most frequent wind components are usually most windy. This fact also confirms the results in Fig. 6. Figure 6 shows the annual course of wind speed under the selected wind directions at both localities. It can be seen that during the whole day the wind speed of WSW wind direction at Skalnaté Pleso is always higher than the long-term average. Similar situation is in the case of the wind speed of S direction at Stará Lesná.

The character of the daily course of the wind speed in the high-mountain massifs depends mainly on the locality in the vertical profile of the mountain

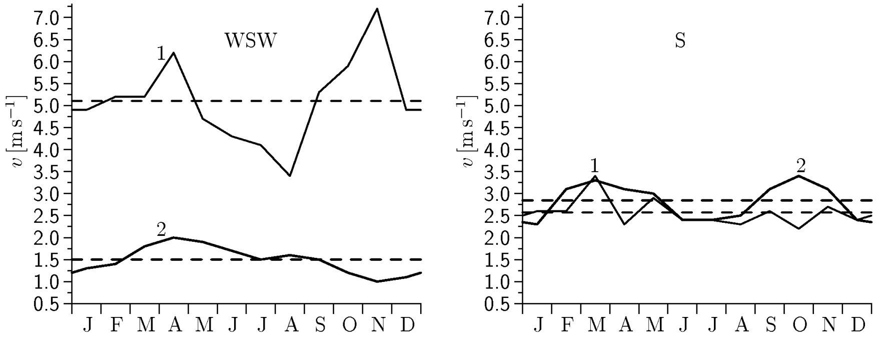

Fig. 6. Annual course of the wind speed v in m s^{-1} of WSW and S wind directions at Skalnaté Pleso (1) and at Stará Lesná (2) during the 1992-2006 period.

range. This fact also confirms the results in Fig. 7. From the course of the curves it can be seen that the wind speed at Stará Lesná has an expressive daily course characterized by one maximum and one minimum. During the daytime, with the sunrise and by the development of convective cloudiness, the wind speed increases. We can see that the highest values of wind speed occur at noon (midday hours), and the mean values are nearly 3.0 m s^{-1} (13 and 14 h). According to the expectation, the minimal values of wind speed occur in the evening and morning hours, and in the interval from 24 to 8 h the values are in range 1.5-1.8 m s^{-1}. On the other hand, the daily course of wind speed at Skalnaté Pleso is not expressive and the daily amplitude is small, only 0.3 m s^{-1}. Here, we can see two maxima: one in the morning from 10 to 13 h and second in the evening from 20 to 23 h. It also confirms that such unexpressive course of wind speed occurs in the transitive level zone, like a transition between lowland type of daily course of wind speed (daily maximum and nightly minimum) and high-mountain type (nightly maximum and daily minimum). Such vertical distribution of daily amplitude of wind speed demonstrates that the vertical stability increasing

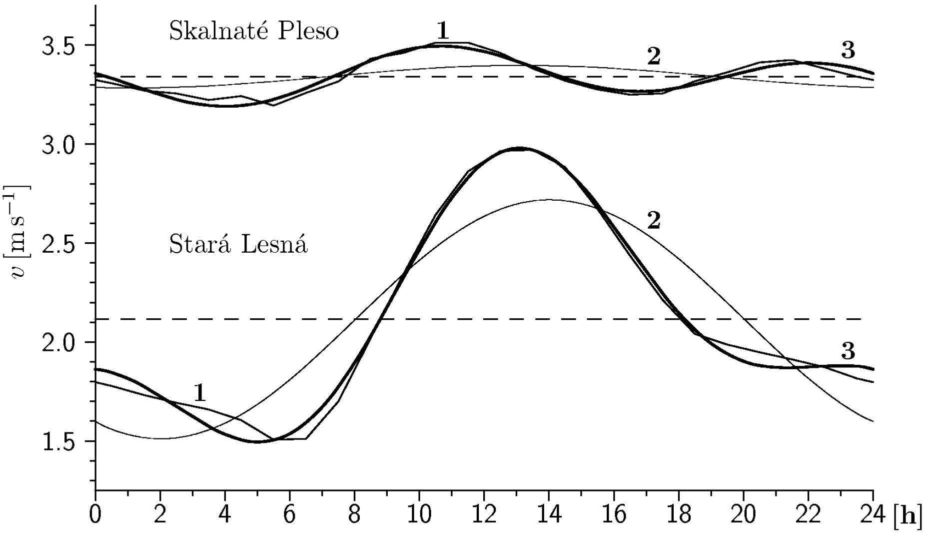

Fig. 7. Periodic daily course of wind speed v in m s^{-1} at Skalnaté Pleso (1) and Stará Lesná (1), and its first (2) and the first two (3) harmonic components during the 1992-2006 period.

of the surface atmospheric layer in the evening and morning hours a thermal turbulence during the daily hours induces the highest relative changes of wind speed in the lower part of the high-mountain massif. The daily course of wind speed at Stará Lesná is typical for the lowland localities in our country.

The comparison of the daily course of wind speed – experimental and theoretical – in Fig. 7 shows that the experimental values of the daily course can be well approximated by the first two harmonic components at both sites. An analytical expression of the daily course of wind speed in Fig. 7 can be written by the first two harmonic components in the form

$$v = 3.444 + 0.057\sin(x + 245°21') + 0.110\sin(2x + 123°43') \ldots\ldots \text{Sk. Pleso}$$

and

$$v = 2.115 + 0.604\sin(x + 232°05') + 0.287\sin(2x + 56°19') \ldots\ldots\ldots \text{St. Lesná}$$

where x is a time angle. It is computed from $x = iz$, $z = 360°/P$, $i = 0, 1, 2, \ldots \mathrm{n} - 1$, if P denotes the length of the period investigated. In this case $\mathrm{n} = 24$, $P = 24$ hours and $z = 360°/24 = 15°$.

Regarding the daily course of wind speed in the case of the selected wind direction (Fig. 8), we can state that during the whole year the mean wind speed values of WSW directions are higher at Skalnaté Pleso than at Stará Lesná. It is interesting that the mean values of S directions at Stará Lesná are around the midday higher than at Skalnaté Pleso.

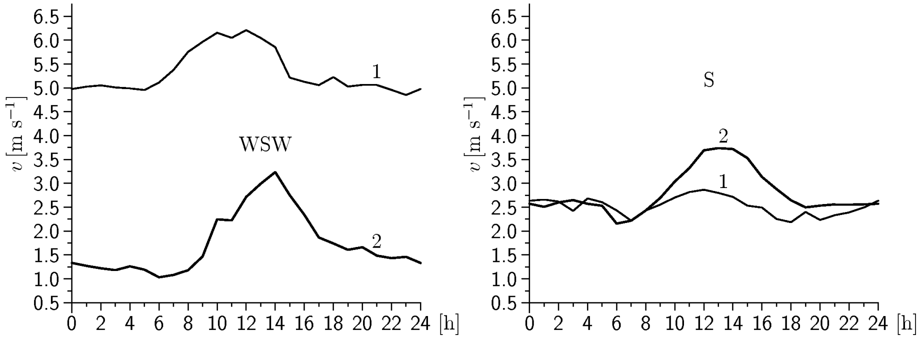

Fig. 8. Daily course of the wind speed v in m s^{-1} of WSW and S wind directions at Skalnaté Pleso (1) and at Stará Lesná (2) during the 1992-2006 period.

From the scientific, as well as the practical aspects, it is interesting to look at the matrix of the hourly values of wind speed in Fig. 9. The concentrated field of curves by cubic splines represents the daily and seasonal variability of wind speed at both the meteorological observatories. The

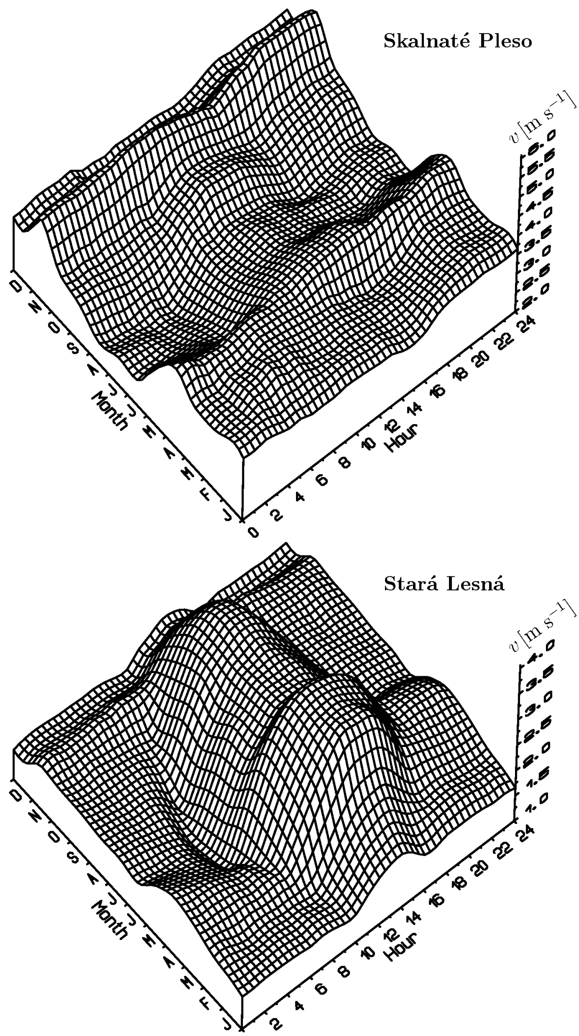

Fig. 9. Time variability of wind speed v in m s^{-1} at Skalnaté Pleso and at Stará Lesná during the 1992-2006 period.

course of the curves confirms that the wind speed variability is characterized by the considerably different daily and annual courses. For example, while at Stará Lesná the daily course is relatively simple in every months of the year, at Skalnaté Pleso it does not have a typical character.

4. Conclusions

By processing the extensive material of wind speed and wind directions at Skalnaté Pleso and Stará Lesná during the 1992-2006 period many statistical characteristics were obtained. For example, it has been shown, in spite of the fact, that the occurrence of calm is more frequent at Skalnaté Pleso than at Stará Lesná (in mean sense), the position of Skalnaté Pleso is windier than Stará Lesná. While Skalnaté Pleso is characterized by prevailing south-western air flow components, at Stará Lesná the most frequent winds are with the south components of air flow. It has been shown that the annual course, as well as diurnal the one, of wind speed at both localities can be approximated by the first two harmonic components.

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