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ACOUSTOOPTICAL AND RADIOOPTICAL METHODS FOR ENVIRONMENTAL STUDIES

Dependence of the Friction Speed on the Wind Speed in the Surface Air Layer

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Abstract—The empirical relationships between the friction speed (dynamic speed) and the crosswind speed are considered for different conditions (time of the day, season, stratification type, observation site, and measurement altitude). Initial experimental data used to derive these relationships were acquired by ultrasonic weather stations operating in the surface air layer at different observation sites.

Keywords: surface air layer, wind speed, friction speed, turbulence

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INTRODUCTION

The friction speed u_* enters into computational schemes used for forecasting the state of the atmosphere (see, e.g., [1–6] and references therein). To find u_*, it is necessary to know the mixed moments of turbulent components of the wind vector. However, the information about turbulence is usually lacking at the initial stage of a forecast. To acquire it, some “external” parameters should be used, for example, probable horizontal wind speed V_h. In this work, we consider empirical relationships $u_*(V_h)$ for different conditions (time of the day, season, and stratification type). The experimental data for the analysis of these relationships were received from ultrasonic weather stations (UWS) [7] operating in the surface air layer at two observation sites: (1) IAO, at the edge of Tomsk (Akademgorodok), on the urbanized territory, 5 m above the roof of the laboratory building of the Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences (IAO SB RAS), 17 m above the underlying surface; (2) BEC—Basic Experimental Complex of IAO SB RAS, natural landscape, large forest opening, measuring altitudes are 5 and 10 m; measuring frequency is 10 times per second (10 Hz). We analyze the experimental data acquired in 2019. The measurements were interrupted for technical reasons. The estimates below were calculated over 10-min intervals.

The friction speed is often calculated by the equation (see, e.g., [8–14])

$$u_* = \sqrt[4]{(\overline{u'w'})^2 + (\overline{v'w'})^2}, \quad (1)$$

though its classic definition has the form [15–17]:

$$u_* = \sqrt{-\overline{u'w'}}. \quad (2)$$

In Eqs. (1) and (2), u', v', and w' are the pulsation components of the longitudinal, cross, and vertical speeds, respectively. The bar above means averaging over a time period. The procedure used for distinguishing the pulsation components of the wind vector is described in [18].

Below, we calculate u_* by Eq. (1). Let us make one more remark about the “classical” specification of the friction speed: its value should be determined in the immediate vicinity of the underlying surface and correspond to the roughness height (parameter) z_0, which is approximately equal to 5–15 cm at BEC and 0.5–1 m at IOA (according to the gradation [19] accounting for the season). For u_* estimates at altitudes $z > z_0$, the term “local values” is often used [5]. Later on, we analyze just the local values of u_*. A detailed study of the measuring altitude dependence of u_* is an individual problem and is beyond the scope of this work.

The main purpose of the study is to consider a possibility of a rough estimate of the friction speed in the surface air layer based on the known (or predicted) data on the horizontal wind speed at an observation site. This can be useful, for example, in the cases where researchers have information only about the average wind speed at this site. An additional task was to generally consider the effect of such external parameters as the season, time of the day, wind direction, and vertical turbulent heat fluxes on the friction speed.

RESULTS

Figure 1 provides for general ideas about u_* and V_h ranges during the first period of measurements (2019).

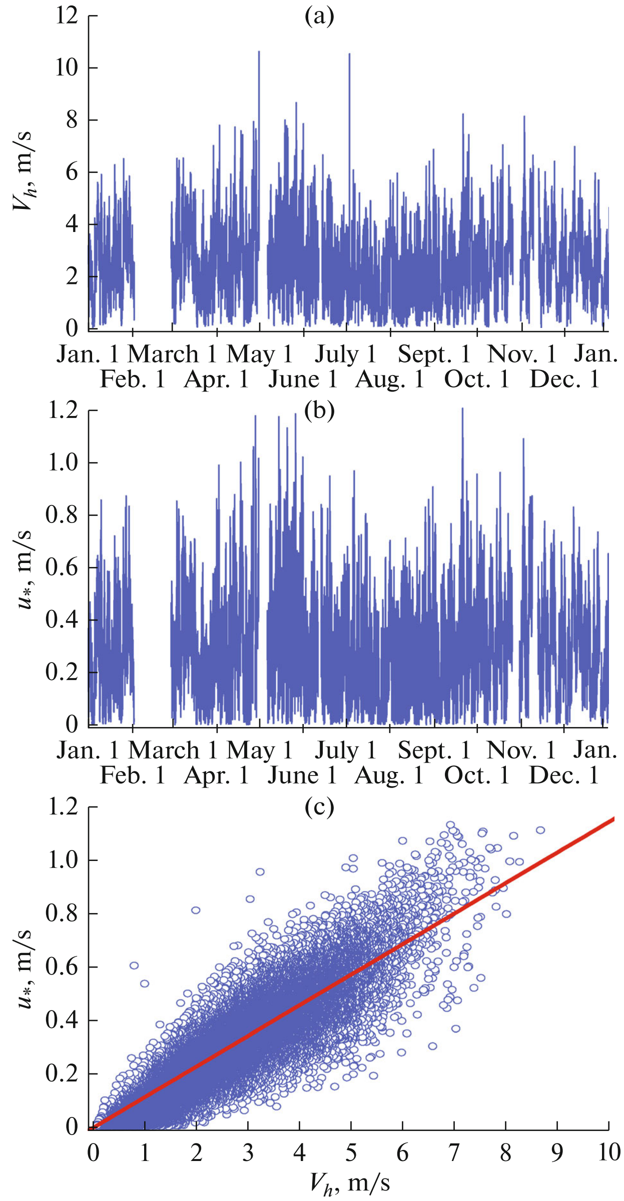

Fig. 1. (a) Wind speed and (b) friction speed measured at BEC_10 m point throughout 2019; (c) dependence of the friction speed on the wind speed throughout the measuring period and its linear approximation (straight line).

It has been plotted for the BEC site at an altitude of 10 m (BEC_10 m) and shows the relationship between u_* and V_h throughout the period and its linear approximation with the determination factor (approximation quality) [20] $k_d \approx 0.94$. The determination factor can vary from 0 (bad quality) to 1 (excellent quality).

The main aim of this work is the study of parameters (slopes) of the relationship approximating lines

$$u_*(V_h) \approx \gamma V_h, \tag{3}$$

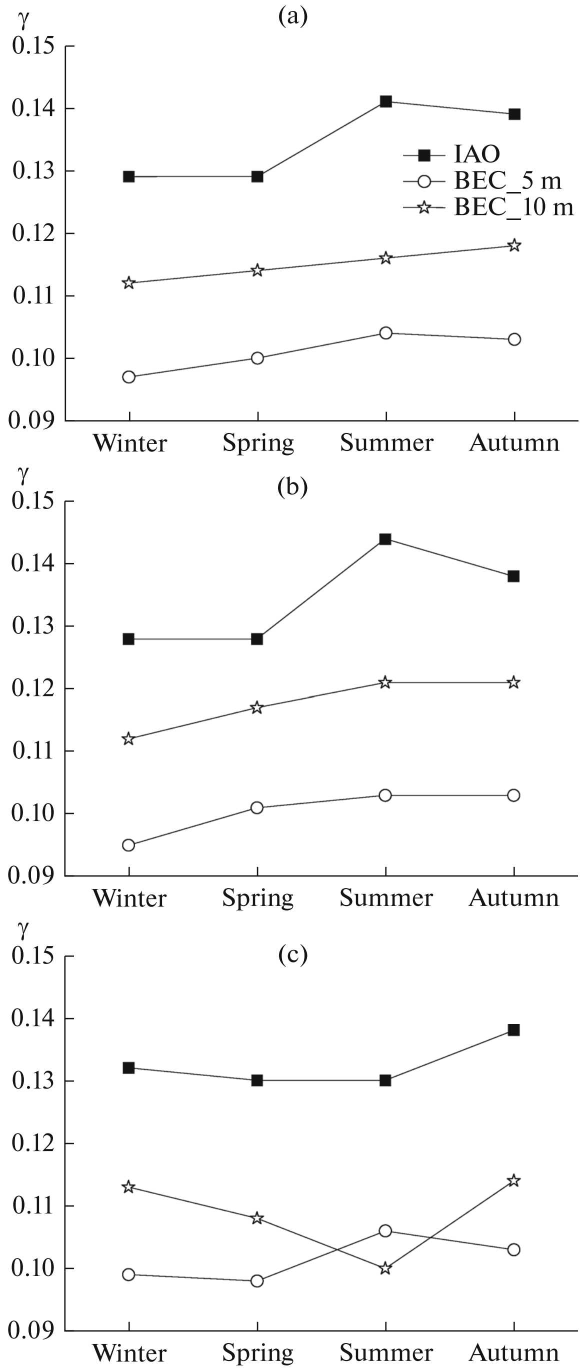

Fig. 2. The approximation parameter versus season from (a) daily (00:00–24:00), (b) daytime (10:00–17:00), and (c) nighttime (22:00–05:00) measurements in 2019.

i.e., the analysis of dependences of the dimensionless factors γ on different conditions. The friction speed is assumed zero at any altitude if $V_h = 0$.

An example of approximation of the dependence $u_*(V_h)$ by Eq. (3) for BEC_10 m (over 2019) is shown in Fig. 1b (straight line), where $\gamma = \gamma_{B10} \approx 0.115$. For BEC_5 m, $\gamma = \gamma_{B05} \approx 0.100$, and for IAO, $\gamma = \gamma_A \approx 0.133$

Table 1. Values of the factors γ and k_{d} and the sample length T (in hours) used for the estimation

Site	Time	Parameter	Winter	Spring	Summer	Autumn
BEC_5 m	00:00–24:00	γ	0.097	0.100	0.104	0.103
		k_{d}	0.95	0.94	0.90	0.94
		T	2616	2042	2072	595
	10:00–17:00	γ	0.0958	0.101	0.103	0.103
		k_{d}	0.95	0.94	0.91	0.95
		T	758	595	607	374
	22:00–05:00	γ	0.099	0.098	0.106	0.103
		k_{d}	0.96	0.93	0.88	0.93
		T	770	594	603	391
BEC_10 m	00:00–24:00	γ	0.112	0.114	0.116	0.118
		k_{d}	0.95	0.95	0.91	0.94
		T	2071	1909	2035	1190
	10:00–17:00	γ	0.112	0.117	0.121	0.121
		k_{d}	0.96	0.96	0.92	0.95
		T	603	554	594	339
	22:00–05:00	γ	0.113	0.108	0.100	0.114
		k_{d}	0.96	0.93	0.86	0.93
		T	611	561	596	359
IAO	00:00–24:00	γ	0.129	0.129	0.141	0.139
		k_{d}	0.93	0.91	0.93	0.93
		T	2674	1953	2129	1342
	10:00–17:00	γ	0.128	0.128	0.144	0.138
		k_{d}	0.93	0.91	0.93	0.93
		T	783	573	620	383
	22:00–05:00	γ	0.132	0.13	0.13	0.138
		k_{d}	0.93	0.92	0.93	0.93
		T	780	570	626	400

(not shown). A similar analysis, but with addition of a free term in the right part of Eq. (3), was carried out in, e.g., [13, 14]. In particular, estimates for the parameters γ in the range ~0.05–0.1 for altitudes of 5 and 10 m are presented in [13] (measurements were carried out within the CASES-99 experiment in October 1999).

Let us now consider the results for some special cases. First, we consider the estimates of γ in different seasons of 2019: winter (January, February, November, and December), spring (March–May), summer (June–August), and autumn (September–October) (Table 1). The values of γ obtained after such a division are collected in the table. Days are additionally divided into daylight and night hours, which are assumed to be from 10:00 to 17:00 and from 22:00 to 05:00 local time, respectively, for all seasons.

According to the results in Table 1, the quality of the linear approximation of $u_*(V_h)$ can be generally considered satisfactory, except for measurements in summer nighttime at the BEC site ($k_{\mathrm{d}} < 0.9$). The statistical reliability of the estimates (the total length of the samples T, over which the statistics was calculated) can also be considered satisfactory.

For illustrative purposes, the coefficients γ_A, γ_{B05}, and γ_{B10} are plotted in Fig. 2 versus season and time of day by the data from Table 1. According to Fig. 2, the friction speed most actively increases with the wind speed at the IAO site (($\gamma_A > \gamma_{B05}, \gamma_{B10}$) in all seasons and at any time of the day. At the BEC_10 m point, the friction speed increases faster with the wind speed than at BEC_5 m, with the exception of the night hours in the summer. Note also that the rate of increase in u_* with an increase in V_h is higher in summer and autumn than in winter and spring. This primarily refers to daytime and estimates of γ over 24 h.

The above results are only general estimates of the characteristics of linear approximation (3) of the function $u_*(V_h)$ and their dependences on the measure-

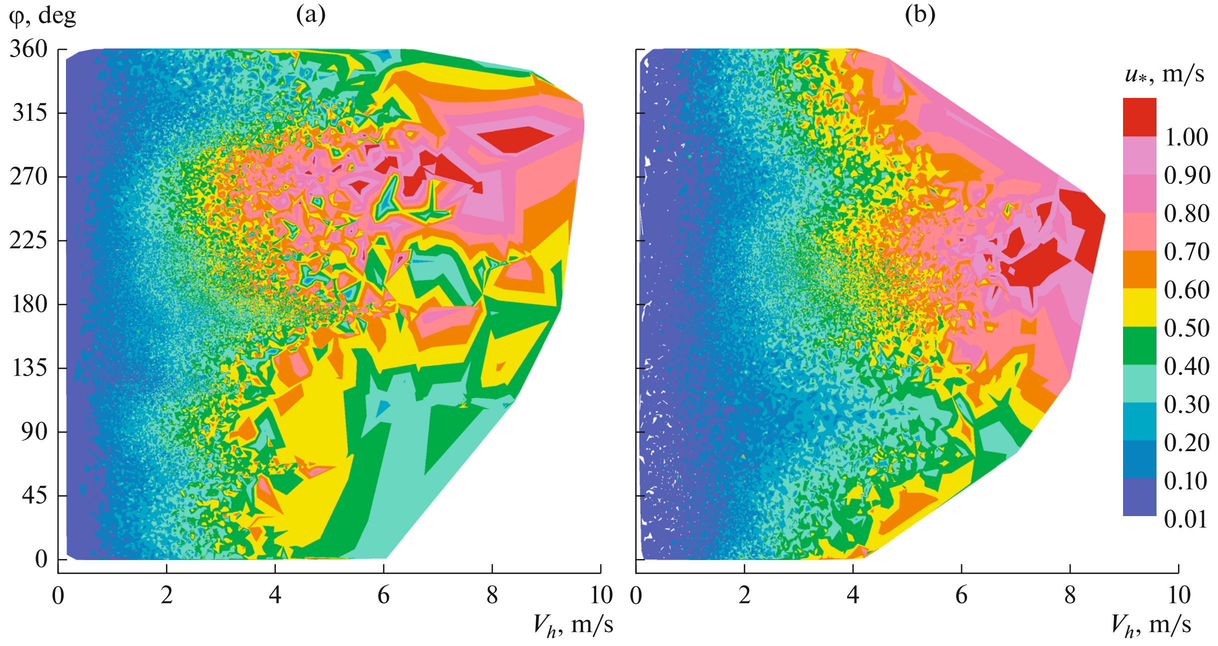

Fig. 3. Correlation between the friction speed and the wind speed and direction at (a) IAO and (b) BEC_10 m sites (φ is the wind azimuth).

ment site, season, and time of day. For a more detailed study of the wind dependence of the friction speed in the surface air layer, it is necessary to consider not only the wind speed V_h, but also other wind characteristics, for example, its direction φ. An adequate parameterization of the function $u_*(V_h)$ is naturally much more difficult to derive in this case, although this can significantly improve the estimate (forecast) of the u_* value based on the known (predicted) wind speed and direction. We previously used a similar approach when parameterizing the relationship between the turbulence kinetic energy and wind speed [21] and showed its efficiency.

In this work, we did not aim to derive possible parameterizations of the function $u_*(V_h, \varphi)$, but only to estimate its general regularities throughout 2019 for observation sites IAO and BEC (measurements at an altitude of 10 m) (Fig. 3).

Certain regularities in the relationship $u_* \leftrightarrow \varphi$ are obvious at both observation sites which, in principle, can be parameterized. However, the analysis of these dependences has not been carried out during this stage.

The influence of the stratification type in the surface air layer on the relationship $u_*(V_h)$ can be estimated from Fig. 2, since it shows the values of γ for nighttime (predominantly stable stratification) and daytime (predominantly unstable or indifferent stratification) conditions. Some difference in the rate of increase of u_* with the wind speed V_h is obvious in the cases selected.

A more detailed pattern of the relationship $u_*(V_h, Q_z)$ (Q_z is the vertical turbulent heat flux, W/m^2) at the BEC_10 m point is shown in Fig. 4. The stratification is stable at negative values of Q_z and unstable (or close to indifferent) at positive Q_z. This example does not show a particular effect of Q_z on u_*. The features of the pattern near its "boundaries" under weak wind may be connected with insufficient statistical availability of the estimates in these conditions. Therefore, we can conclude that there is no explicit need in accounting for Q_z in the simplest parameterization of the relationship $u_*(V_h)$.

CONCLUSIONS

Let us formulate the main conclusions from the work.

The main purpose of the analysis was to verify a possibility of rough estimation of the local friction speed (dynamic speed) in the surface air layer based on the measured (or predicted) horizontal wind speed. A linear relationship between these parameters was used for the estimation. As a result, the gradients of the increment of the friction speed were calculated and analyzed for different seasons and different times of the day in an area with a natural landscape at altitudes of 5 and 10 m, as well as in an urbanized area at an altitude of 17 m from the underlying surface. The quality of linear approximation of the dependence under study can be considered satisfactory in almost all cases considered. The resulting estimates of rates of increase

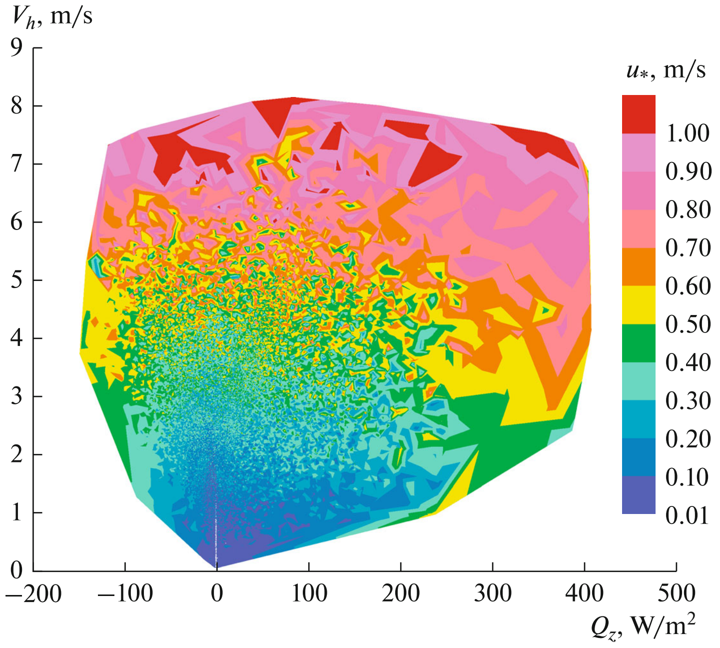

Fig. 4. Correlation between the friction speed and the wind speed and vertical turbulent heat flux at BEC_10 m point.

coincide in order of magnitude with the results of other authors.

The influence of the wind direction and surface vertical turbulent heat fluxes and the necessity of taking them into account when estimating the friction speed versus the wind speed are briefly considered. It is found that it is desirable to take into account the wind direction, while the effect of turbulent heat flux in the surface air layer can be ignored in this approach.

The results of our work naturally correspond only to specific observation points. However, we hope that the general approach to rough estimation of the friction speed from the average wind speed is applicable to other observation sites.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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