Determination of the turbulent fluxes of heat and momentum in the ABL by ground-based remote-sensing techniques (a...

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Remote Determination of Momentum-Flux Profiles in the Lower Atmospheric Boundary Layer

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Abstract—An acoustic locator—a sodar—is a unique instrument for getting the objective characteristics of the current state of the atmospheric boundary layer (ABL) owing to a combination of such properties as remoteness, mobility, resolution, and information content. This study demonstrates the capabilities of a sodar to obtain data on the second moments of the field of wind-velocity fluctuations, in particular, the profiles of momentum flux in the lower ABL, which are very important in practical applications. A corresponding method is described, and the results of its experimental verification and some examples of its application under the conditions of different ABL stratification are presented.

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1. INTRODUCTION

Mathematical models of different complexity are used in solving practical problems related to atmospheric motion. The current models of atmospheric processes make it possible to obtain sufficiently accurate real-time predictions of a number of phenomena, including the transfer of pollutants. However, such models require a large amount of empirical data. It is better if these data are obtained in real time for a specific region to be predicted.

The objective of this study is to show that a sodar is a compact and simple instrument that is not inferior in terms of spatial resolution to, for example, a meteorological tower but is much cheaper to purchase and operate and that makes it possible to obtain empirical data (for atmospheric dispersion models) with the characteristic degree of efficiency and spatial resolution. In addition to the conventional direct use of sodar data [1] (for example, the use of the vertical profile of wind velocity in models of pollutant transfer), after some additional echo-signal processing, it is also possible to obtain the vertical profiles of the quantities such as, the turbulent viscosity coefficient or momentum flux, which are very important for these models.

In the absence of meteorological towers, researchers try to use data obtained from standard meteorological observations. On the basis of these data, the vertical profiles of the above quantities are obtained with the aid of empirical dependences, parameterizations, and semiempirical formulas [2]. However, as noted in [2], the accuracy of such a representation leaves much to be desired. Meanwhile, after the use of the methods of echo-signal processing that are proposed in this study, the data of acoustic remote sensing make it possible to bridge this gap.

On the basis of the results obtained in the Zvenigorod-2005 experiment, this study demonstrates the potentialities of the LATAN-3 sodar developed by R.D. Kouznetsov with consideration for the necessity of measuring wind-velocity fluctuations.

2. PROPOSED METHOD

2.1. Assumption 1

The fact that a standard three-component sodar adequately measures the profiles of mean wind speed and direction has been generally recognized and repeatedly supported by experimental data [3, 4]. The same cannot be said of fluctuation components [5, 6].

A direct determination of different components of the turbulent stress tensor from data obtained with a conventional three-component sodar is hardly possible. Such an attempt was made in [7] with the aid of a more complex five-component instrument. However, as is shown below, the variances of wind velocity along each of the beams of a three-component monostatic sodar can be adequately determined, at least, for a sodar with the proposed architecture and method of echo-signal processing.

To obtain detailed information on fluctuations in wind-velocity components USA-1and air temperature in the surface air layer, ultrasonic thermometers–anemometers (METEK GmbH, Germany) [8] with improved algorithms of processing data on wind-velocity and air-temperature fluctuations and the corresponding second moments were included in the equipment to carry out a field experiment at the

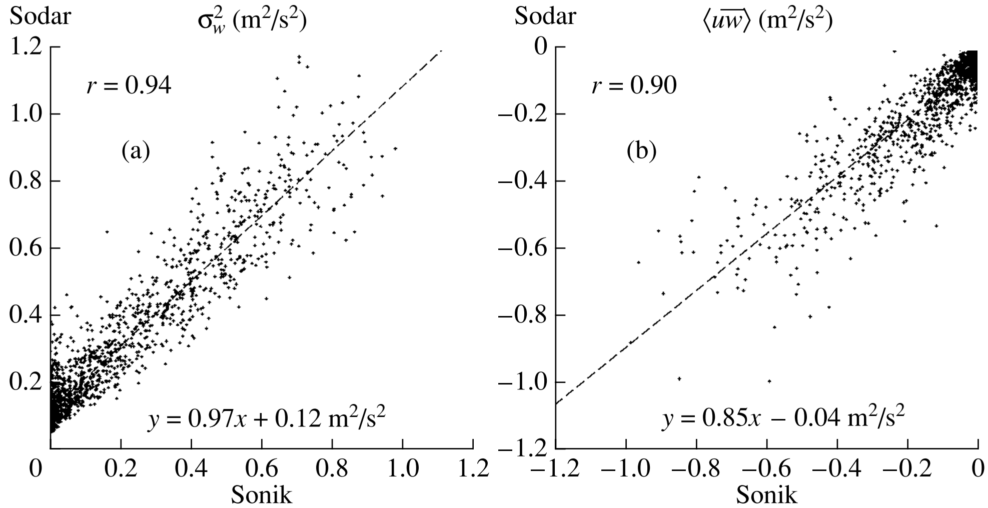

Fig. 1. Comparison of the results of measurements of (a) the variance of fluctuations in the vertical wind-velocity component σ_w^2 and (b) the momentum flux $\overline{uw}$ with an ultrasonic thermometer–anemometer and with the method of acoustic remote sensing.

Zvenigorod Scientific Station (ZSS) of the Oboukhov Institute of Atmospheric Physics, Russian Academy of Sciences. The data on the second moments of the fluctuations and on moving-air temperature that were obtained from simultaneous measurements with the ultrasonic thermometers–anemometers were used to verify sodar data.

Figure 1a presents the results of verifying the quality of sodar data on the variance of the vertical wind-velocity component through their comparison with the data obtained from contact measurements with the USA-1 anemometer (denoted as Sonik in the figure). There is a good agreement between the data obtained with these instruments and the reference data obtained with the USA-1 ultrasonic anemometers. The corresponding correlation coefficient is 0.94.

The problem of agreement between data obtained with different instruments arises from a significantly larger spatial averaging of the wind field in the method of acoustic remote sensing as compared to measurements with an ultrasonic anemometer. In addition, the sodar causes a strong truncation of the high-frequency portion of the spectrum of recorded fluctuations, a limitation that must affect the results of measurement of fluxes and variances primarily at the instants of an abrupt restructuring of air flow (see, for example, [9]). The data given in Fig. 1a (a monthly series with a half-hour averaging, Zvenigorod 2005) allow one to conclude that sodar data on the variance of vertical wind-velocity fluctuations are reliable outside the zones of an abrupt (in time) restructuring of air flow in the ABL. Some overestimation (by the sodar) of σ_w^2 is apparently a systematic error, and the correction -0.08 m^2/s^2 (the minimum value of σ_w^2 measured by the sodar) is introduced in all further calculations. The sodar adequately measures the normal (in our case, along the direction specified by experimental conditions) component of the tensor of turbulent Reynolds stresses [10] (the variance of the vertical wind-velocity component).

A similar conclusion can be drawn for the rest of the beams because the design of antennas, the algorithms of data processing, and the channels of sodar electronics are identical for all beams. Thus, the assumption that sodar data on the variances of beam wind-velocity components may be used to determine turbulence parameters is supported experimentally. The data on wind-velocity fluctuations that are obtained only with a vertical antenna are used in the proposed method; however, in further studies of the atmospheric turbulence with sodars, it is expected that the data obtained with inclined antennas will be taken into account as well.

2.2. Early Proposals for a Neutrally Stratified ABL

An attempt was made in [12] to obtain the vertical profiles of turbulence characteristics, in particular, the turbulent kinetic energy b [11] and the shear stress in the ABL on the basis of data from acoustic remote sensing. The Kolmogorov–Prandtl constant C_{KP} entering the parametric determination of the rate of dissipation of turbulent kinetic energy [11] characterizes the ratio between the energy b and turbulent momentum flux under the conditions of a neutrally stratified ABL. According to experimental data [12], the constant C_{KP} proved to be 2.1. However, the accuracy in determining the energy b from the sodar data used by us turns out to be insufficient for practical applications [6].

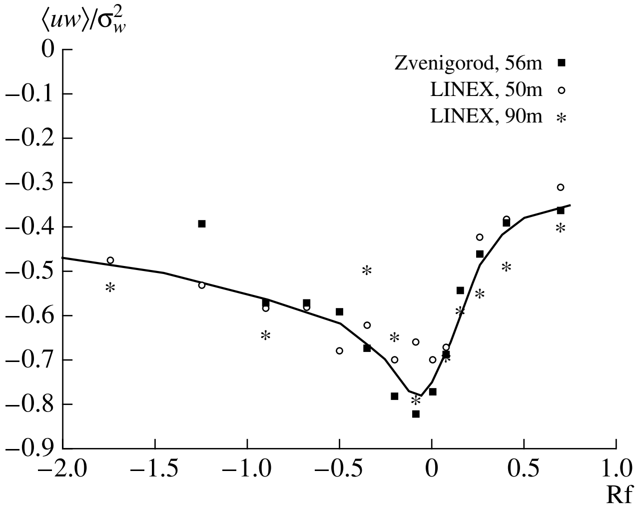

Fig. 2. Experimental estimate of the universal function F_{mf}(Rf) from different measurement data and an approximating function. The data obtained in the Zvenigorod-2005 and LINEX-2000 experiments are integrated. Each point in the graph is the result of averaging over 20–40 half-hour measurement runs.

In processing a large body of experimental data, the following assumption significantly simplifying the analytic apparatus of solving the problem was made: the tangential component of the Reynolds stress tensor with respect to the vertical (the turbulent momentum flux $\overline{uw}$) is proportional to its normal component (the variance of vertical wind-velocity component σ_w^2).

Experimental dependence of the universal function F_{mf}(Rf) on the local Richardson number determined from (1)

Rf	F_{mf}(Rf)	Rf	F_{mf}(Rf)
–5.4	–0.27	0.0	–0.8
–2.0	–0.47	0.1	–0.7
–1.5	–0.5	0.3	–0.42
–1.0	–0.55	0.5	–0.38
–0.5	–0.62	0.7	–0.36
–0.25	–0.7	1.0	–0.34
–0.1	–0.78		
0.0	–0.8		

2.3. Assumption 2

The assumption made in [9] suggests that a universal function exists that depends only on the local parameter of stratification and that allows the quantity $\overline{uw}$ to be calculated from the known value of σ_w^2. Here, the Richardson flux number Rf was chosen as a local parameter. By definition [11],

$$\mathrm{Rf} = \frac{g}{\Theta}\frac{\overline{w\theta}}{\overline{uw}\partial V/\partial z}, \quad (1)$$

where g is the acceleration of gravity, $\partial V/\partial z$ is the wind-velocity gradient, Θ is the air temperature, $\overline{w\theta}$ is the turbulent temperature flux, and Rf is the ratio of the energies (b) generated through buoyancy forces and through wind shear. Analogously to the Monin–Oboukhov parameter z/L of similarity theory, Rf can be used as a stability parameter.

Let us introduce the universal function F_{mf}(Rf) such that

$$\overline{uw} = \mathrm{sgn}\left(\frac{\partial V}{\partial z}\right)F_{mf}(\mathrm{Rf})\sigma_w^2. \quad (2)$$

If the form of F_{mf}(Rf) is known and data on the Rf profile are available, the profile of vertical momentum flux can be determined from (2) on the basis of available data on the σ_w^2 profile. Data on the wind profile and vertical temperature and momentum fluxes are required to calculate Rf. The wind profile can be obtained from remote sensing data. If the temperature flux is estimated in some way, Eq. (2) can be treated as an equation for $\overline{uw}$.

The data obtained with ultrasonic thermometers–anemometers in the Zvenigorod-2005 experiment were processed in accordance with (1) and (2) and together with data from [9] (see Fig. 2). The dependences presented in [9] were obtained from tower measurements over a uniform ground surface (the LINEX-2000 experiment). It should be noted that, in all calculations by the aforementioned formulas, the magnitude of the velocity gradient was substituted into these formulas. Thus, in the calculations, the turn of the vector of mean wind velocity with height was taken into account also, a circumstance that is important outside the surface air layer.

One could try to represent the results with an interpolation formula; however, it is easier to use a piecewise-linear approximation of dependence (2) in accordance with the table, because, in any case, final calculations are carried out with the aid of a computer.

Now, using the available function F_{mf} (Rf) (see table), one can estimate the turbulent heat flux $\overline{uw}$ from measurements of σ_w^2. To obtain the vertical profile of shear stress, it is necessary, in some way, to specify the profile of the turbulent temperature flux $\overline{w\theta}$ in Eq. (2). The profile $\overline{w\theta}$ can be estimated, for example, from measurements of the turbulent heat flux at the surface if this flux is assumed to be the quantity linearly varying from its surface value to zero at the mixing-layer height [2]. This height can be determined with a sufficient accuracy from a sodar echogram.

If the heat flux $\overline{w\theta}$ at a given height and the sodar value of the variance of vertical wind-velocity component σ_w^2 are known and the tabular or graphic representation of the function F_{mf}(Rf) is taken into account, it is possible to solve Eq. (2) for the unknown $\overline{uw}$. Since Rf and, hence, F_{mf}(Rf) depend on $\overline{uw}$ in a complicated manner, it is reasonable to solve Eq. (2) numerically. This procedure was performed for each sounding level.

The results of comparison between the values of $\overline{uw}$ (a monthly series with a half-hour averaging, Zvenigorod 2005) obtained in such a way from sodar data and the corresponding values from USA-1 local tower measurements are given in Fig. 1b.

3. ZVENIGOROD-2005 EXPERIMENT: INSTRUMENTS AND TERRAIN

The experiment was carried out at the ZSS during 30 days in July 2005.

The LATAN-3 sodar used in the experiment is a three-component Doppler acoustic locator with a data-processing channel switched sequentially between antennas. The angle of deviation of the axes of inclined antennas from the vertical was 30°. In the course of the experiment, the operating frequency of a transmitted pulse was 1700 Hz, and the duration of a sounding pulse was 0.1 s, which provided a vertical sodar resolution of 20 m. The extension of the dead zone of the instrument was approximately 30 m. A complete cycle of transmitting three sounding pulses (along three directions) was 15 s. To estimate the vertical wind velocity in the spectrum of a received signal, the ±30-Hz band centered at the transmitted frequency was used.

As for analog electronics, only the antenna amplifier is used in the LATAN-3 receiving channel; the rest of the functions of echo-signal processing are performed by a sound card of the computer and its software. A detailed description of the instrument design and the features of its realization are given in [13].

The ZSS is located at a distance of 50 km from Moscow in a weakly rough terrain with widely spaced low-rise buildings and small forest tracts. In addition to the LATAN-3 sodar, a meteorological tower with USA-1 ultrasonic thermometers–anemometers at levels of 6 and 56 m was set up at the ZSS, so that the data of sodar measurements could be compared to the data of measurements with ultrasonic anemometers.

4. ZVENIGOROD-2005 EXPERIMENT: MEASUREMENT RESULTS

To represent experimental data and to demonstrate daily variations in parameters, the data obtained on July 10, 2005, were chosen from the whole set of measurement data. This day was characteristic of the measurement period in daily variations in the air temperature and heat flux, in the prevailing wind direction and speed, in the lifetime of stable or unstable stratification, and in the shape of a sodar echogram. The measurement data were averaged every half hour, a procedure that is often used in meteorology and makes it possible to obtain stable mean values on the one hand and not to lose the indices of temporal variability of averaged ABL characteristics on the other.

The ABL evolution during this day is shown in Figs. 3a (echogram), 3b and 3c (the averaged hourly profiles of wind velocity and σ_w^2, respectively, according to sodar data), and 3d (time variations in air temperature and the heat flux Hf $= C_p\rho\overline{w\theta}$ according to USA-1 anemometer data). The scatter of points in the profiles obtained from sodar data increases in their upper portions relative to their lower portions, a result that is due to the quadratic decrease of the intensity of the echo signal received by the sodar and, correspondingly, by a decrease of the signal-to-noise ratio and an increase of measurement errors with increasing observation height.

On the basis of a sodar echogram, vertical wind-velocity profiles, and the results of tower measurements of air temperature and vertical heat flux (see Fig. 3), it is possible to distinguish the following distinctive time intervals.

1. The stably stratified ABL (00:00–06:00 and 23:00–24:00) is characterized by a negative heat flux. The ground surface is colder than the ABL, and the heat flux into the surface suppresses turbulence generation. The corresponding Richardson number is positive. The air temperature decreases in time almost linearly (about –0.5 deg/h). In the corresponding portion of the echogram, a dense black layer is seen in the lower region; its height almost coincides with the height of the mixing layer.

2. The unstably stratified ABL (07:00–20:00, from sunrise to sunset). The ground surface is heated by solar radiation, a phenomenon that results in both turbulence generation through buoyancy forces and initiation of a free-convection motion. The latter occurs in the layer adjacent to the ground surface (06:00–08:00) and then extends to the entire boundary layer

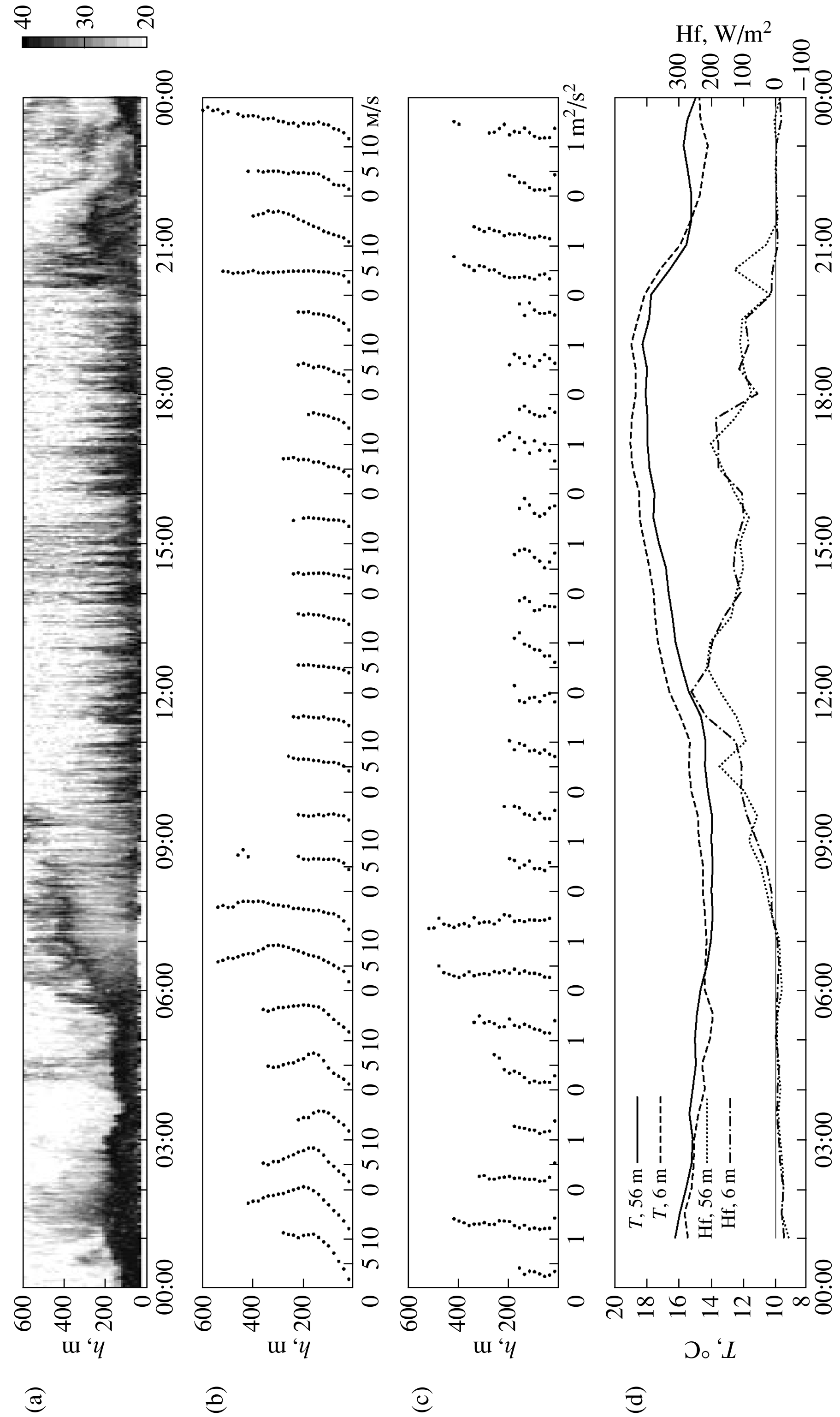

Fig. 3. ABL state during July 10, 2005: (a) sodar echogram (the darkening scale denotes the level of a signal in decibels), (b) horizontal wind-velocity profiles, (c) profiles of the variance of the vertical wind-velocity component σ_w^2, and (d) time variations in air temperature T and heat flux Hf.

(09:00–20:00). The measured air temperature increases with time, and the heat fluxes are very large.

3. The neutrally stratified ABL is formed during short transition periods at about 07:00 and about 20:00 (in the echogram, the light zones throughout the height of the layer). The indicated periods correspond to the times of sunrise and sunset and are characterized by a vanishing heat flux from the ground surface and an almost time-unvarying air temperature.

4. A low-level jet stream is clearly seen in the wind-velocity profiles (Fig. 3b) from 00:00 to 07:00. In the manuals on calculation of pollutant transfer, this phenomenon is usually excluded from consideration (see, for example, [2]) because it is believed that the simulation of such a phenomenon is very complicated, whereas turbulent transfer in the lower ABL is strongly decreased. It is recommended to assume that the wind velocity at a height above 200 m is constant, an assumption that cannot be always justified. For example, as may be seen from the given profiles, the wind velocity decreases significantly (approximately by half as compared to its maximum) with height, while turbulent exchange is very small in the lower ABL but increases up to values characteristic of neutral stratification above the maximum of wind velocity. The indicated features may prove to be important during simulation of the ABL.

For each of the above intervals, the vertical profiles of the magnitude of wind velocity and the variance of vertical wind velocity (both measured directly with a sodar) and of the shear stress (calculated from sodar data according to the method described above) and, hence, the turbulence viscosity coefficient K_t (calculated according to a classical definition [11]) were constructed (Fig. 4):

$$\overline{uw} = -K_t\frac{\partial V}{\partial z}. \qquad (3)$$

The profiles of wind direction are omitted because the variability of wind direction did not exceed 15° during the day under consideration and had a smooth character both in time and height. The wind was generally directed northward. In Fig. 4, the solid lines denote the wind-velocity profiles calculated from the interpolation formulas.

The following moments of time were chosen as the characteristic ones: 02:00 (stable stratification, jet stream), 07:00 (stratification close to neutral, the jet stream is displaced into the upper ABL by an expanding convection), and 15:00 (convection with an expanded turbulent motion and high values of heat and momentum fluxes).

The wind profiles were approximated by analytic logarithmic dependences with the parameters u_* and z_0 obtained from the lower 9–15 points of sodar measurements through the least-squares method. Such a representation was used to more accurately calculate the vertical gradient of the wind-velocity magnitude $\partial V/\partial z$ from an analytic function approximating experimental data, but not directly from the experimental points, because the value of the unknown gradient plays a significant role in the equations to be solved. In the same way (with the least-squares method) and for the same reason, the parameters of the approximating analytic function were found for the upper region of the profile of wind velocity in the low-level jet (Fig. 4a). As an approximating function for the jet profile, the corresponding theoretical dependence was used [14]. Then, the resulting profile was joined in value with the underlying logarithmic profile at the height of vanishing heat flux.

The model heat fluxes that are necessary for calculation of the Richardson number were estimated in two ways for reliability: (i) routinely, from the mixing-layer height obtained from a sodar echogram [14], and (ii) in a stably stratified ABL (02:00), from the linear trend of air temperature (0.5 deg/h) with the use of the phenomenological heat-transfer equation and the heat-flux value obtained from measurements with an ultrasonic thermometer–anemometer (–24 W/m^2 at a height of 56 m), one can obtain the coefficients of the linear height dependence of heat flux. The height at which the calculated flux vanishes coincides with the mixing-layer height (about 200 m) obtained from the given echogram (Fig. 3a).

Moreover, the jet-stream profile (Fig. 4a) is representative of variations in turbulence characteristics along the vertical and can be used to verify the assumptions used in both the turbulence model and the method of sodar-data processing. In particular, in accordance with the simplified turbulence models, such as the classical Boussinesq model with the use of the concept of the turbulent viscosity coefficient [10], in the region of a zero velocity gradient (in the vicinity of the profile's "nose"), this coefficient must tend to infinity, so that the replacement of such a model in the region under consideration is required. In fact, the shear stress in the vicinity of the maximum velocity of the jet-stream profile must pass through zero and change its sign so that the turbulence could be generated further by velocity shear despite the change in the sign of the velocity gradient, a result which is taken into account in the proposed relationship (2).

Turbulence generation by wind-velocity shear actually decreases; moreover, in the region under consideration, turbulence generation also tends to zero owing to buoyancy forces. However, the diffusion mechanisms continue to work, thus leading to a continuous supply of turbulent energy into the region with a zero velocity gradient, so that σ_w^2 does not vanish (see Fig. 4a), a result that, in turn, does not agree with Eq. (2). It is evident that, for the given example, the boundary-layer structure is characterized by more than one length scale and more than one velocity

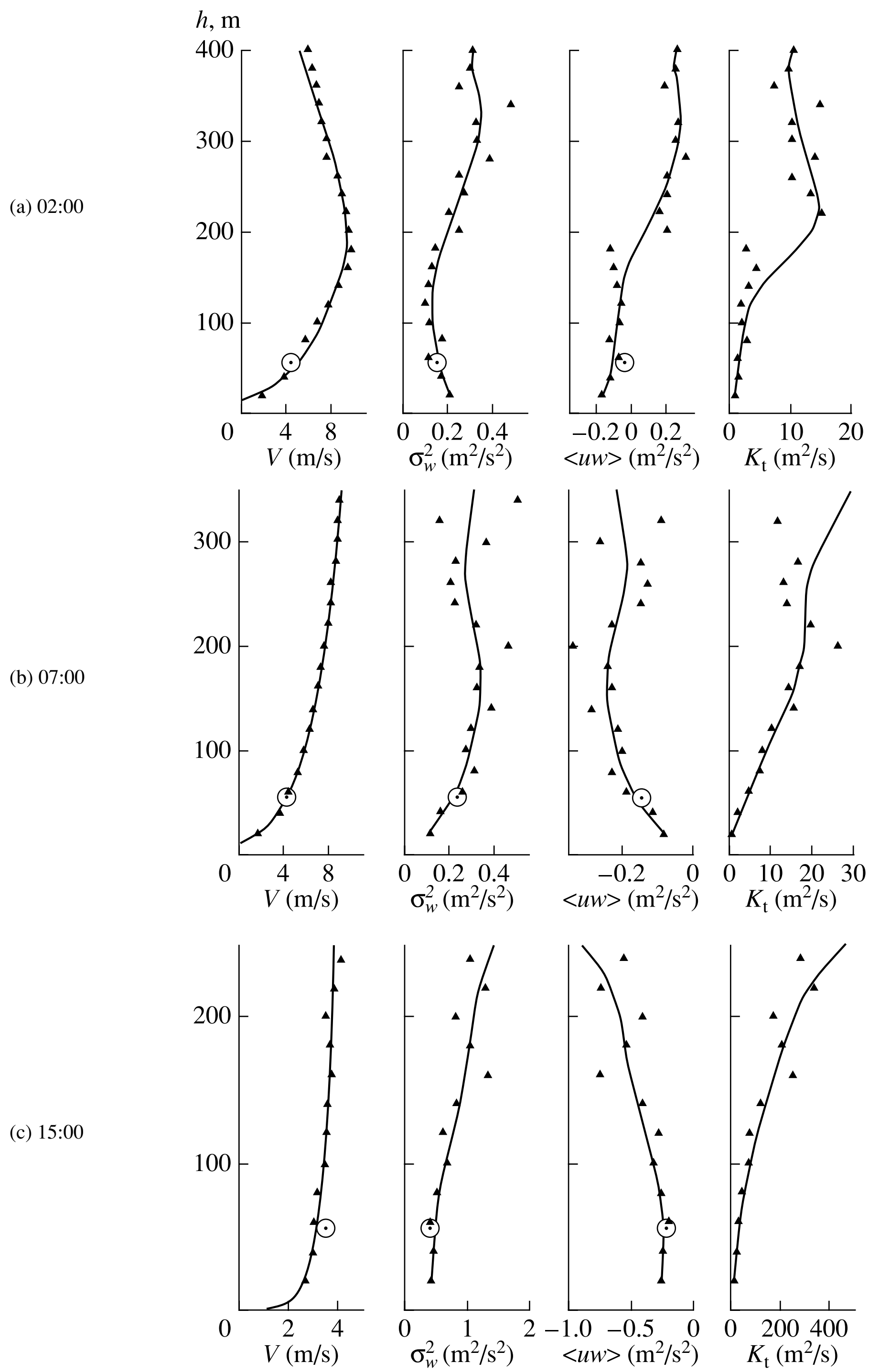

Fig. 4. Examples of the profiles of wind velocity, variance of its vertical component, turbulent momentum flux, and coefficient of turbulent viscosity, which were obtained from sodar measurements under different conditions: (a) stable stratification (02:00); (b) morning heating (07:00), neutral stratification at the bottom; and (c) unstable stratification (15:00). The points in circles correspond to the data obtained from contact measurements with a USA-1 anemometer.

scale, and, for an adequate description of such turbulence, simple assumptions, among which is the proposed relation (2), are insufficient. To determine the shear stress from sodar data, it is necessary to use more complicated models.

For neutrally stratified (Fig. 4b) and unstably stratified (Fig. 4c) ABLs, the result is quite predictable. The velocity profile is well approximated by the logarithmic law, and the shear stress in the unstably stratified layer increases several times as compared to a stable or neutral stratification.

In Fig. 4, the profiles of the horizontal wind velocity V and the variance of its vertical component σ_w^2 were directly measured by the sodar. The profiles of the momentum flux $\overline{uw}$ were calculated from Eqs. (1) and (2) with consideration for the V and σ_w^2 profiles and the estimate of the profile of the turbulent temperature flux $\overline{w\theta}$. The value of the latter in the lower ABL was determined directly from measurements with the USA-1 anemometer, and the vertical profile was constructed (in accordance with the recommendation given in [2]) as linearly decreasing with height and vanishing at the upper boundary of the mixing layer. The height of this layer was determined from the sodar echogram given in Fig. 3a and from the estimates of temperature trend and heat fluxes obtained from contact measurements with the USA-1 anemometer. The profiles of the turbulent viscosity coefficient K_t were calculated in accordance with the definition from [11] (see formula (3)).

Under the conditions of neutral stratification (Fig. 4b), in the K_m profile calculated from sodar data, a portion of the linear height dependence of this coefficient is clearly defined and represents the well-known approximation [10, 11]. Such a result additionally supports the validity of the above assumptions and the proposed algorithms of sodar-data processing.

5. CONCLUSIONS

The proposed method is easy to use and yields reasonable results under quasi-stationary conditions for neutrally and unstably stratified boundary layers. This method can be used for the lower stably stratified boundary layer as well. In the cases of low-level jets, it is necessary to use more complicated turbulence models to obtain a close approximation during simulation of pollutant transfer.

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