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Diurnal dynamics of the reduced turbulent kinetic energy in the atmospheric boundary layer from minisodar measurements

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Abstract: Based on acoustic remote measurements of the diurnal dynamics of three wind velocity components and their variances in the lower 200-meter layer of the atmosphere, the kinetic energy of the atmosphere reduced to unit mass is estimated, with a particular emphasis on the turbulent kinetic energy component. For a 24-h period of continuous minisodar observations, the turbulent energy in the surface layer was very low to altitudes of ~50 m. With increase in altitude from 50 to 100 m, the turbulent kinetic energy quickly increased, and at altitudes exceeding 100 m, its fast growth is observed, with a maximum at altitudes of 150–200 m. Essential influence of time of the day on the results of observations was established. Thus, at night at the same altitudes the kinetic energy density first did not exceed 20 J/kg, and its moderate growth (from 20 to 50 J/kg) was observed with increasing time. In the morning, the maximum energy density of air masses was observed. After sunrise, the turbulent component of the kinetic energy density rapidly decreased. It is essential that the system the Earth surface – the near-ground air layer tends to an equilibrium state. As a consequence, the spread of values of the turbulent energy is reduced. The most significant changes were observed at altitudes in the range 100–200 m. It is essential that at altitudes up to 50–100 m, time of the day had no significant effect, because at these altitudes the turbulent energy was low and remained practically unchanged with time. Irrespective of time of the day, the maximum turbulent energy was observed at altitudes in the range 100–200 m that pose the greatest danger to small flying objects. The corresponding estimations are presented.

Keywords: atmospheric boundary layer; reduced kinetic energy of the atmosphere; turbulence kinetic energy; diurnal dynamics; acoustic sounding; minisodar

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1. Introduction

The kinetic energy plays an important role in physics of the atmospheric boundary layer (ABL), investigation of its structure and dynamics, development of adequate physical representations, and construction of realistic mathematical models [1–3]. It is one of the main characteristics of the ABL, defining both global and local circulations in the atmosphere and momentum, heat, and mass transfer. Moreover, it is necessary for the forecasting and calculating fields of meteorological parameters and diffusion of pollutants and for analyzing and forecasting conditions of acoustic radiation propagation. The importance of ABL investigations has significantly increased recently in connection with revolutionary development and application of unmanned aerial vehicles (UAVs), especially mini and micro dimensional UAVs made of light materials and subject to strong influence of the turbulent kinetic energy [4].

A number of lidar, sodar, and radar methods are being developed for measuring and forecasting average values and variances of the wind velocity components in the ABL (for example, see [5–8]). Each of them has its own advantages and disadvantages. For example, the refractive index of sound waves is about 10^6 times higher than of radio or optical waves. Strong interaction of sound waves with the atmosphere and the ability to obtain information in real time and round the clock with much higher spatial and temporal resolution make sodars unique tools for investigation of the wind velocity vector field in the ABL. The application of the Doppler acoustic radars (sodars) allows simultaneously long time series of continuous observations of vertical profiles of both average values and variances of three wind velocity components to be obtained in real time [3, 7, 9]. The data with high spatial (up to several meters) and temporal resolution (statistically reliable profiles of wind velocity components with averaging from 1 to 30 min) can be obtained, and their spatiotemporal dynamics can be analyzed. As a result, this allows the data of minisodar measurements to be used for estimating the kinetic energy of both average and turbulent motions of air masses in the ABL. Thus, in [9] results of preliminary analysis of the spatiotemporal dynamics of the kinetic energy of the atmosphere reduced to unit air mass retrieved from data of minisodar measurements were presented.

The paper presents the results of investigations of the kinetic energy $E(z, t)$ of the ABL at the altitudes $z = 5$–200 m from minisodar measurements with the spatial resolution $\Delta z = 5$ m in the morning, daytime, and evening hours and also its diurnal hourly dynamics. The relative contributions of the energy of average motion and of the turbulent kinetic energy are also analyzed.

2. Applied methods and approaches

The kinetic energy of the ABL $E_\Sigma = mV^2/2$ is defined by the energy of motion of air masses – the wind energy. Below we consider the kinetic energy of the ABL reduced to unit air mass $E = E_\Sigma / m$ and measured in m^2/s^2 (m^2/s^2 = J/kg). It is natural that the regularities in the spatiotemporal behavior of the reduced kinetic energy will fully concern the total kinetic energy. For this reason, below we use the term *kinetic energy* for the kinetic energy per unit air mass. It is equal to the sum of two components: the kinetic energy of ordered motion E_{MKE}, associated with the average wind velocity, and the kinetic energy of turbulent motion of air masses E_{TKE}, associated with the wind velocity variance, and can be written as [1–3]

$$E = (E_{MKE} + E_{TKE}) / m. \quad (1)$$

A Doppler acoustic radar (sodar) allows long-term continuous observations to be performed of the spatiotemporal dynamics of both average values and variances of the three wind velocity components in the ABL and hence the spatiotemporal dynamics of the kinetic energy of the atmosphere to be investigated. The kinetic energy components E_{MKE} and E_{TKE} were calculated from the data of minisodar measurements using the formulas [9, 10]:

$$E_{\mathrm{MKE}}(z_j,t_k)=\left[\left\langle V_x(z_j,t_k)\right\rangle^2+\left\langle V_y(z_j,t_k)\right\rangle^2+\left\langle V_z(z_j,t_k)\right\rangle^2\right]/2$$
$$=\frac{1}{N^2}\left[\left(\sum_{i=1}^{N}V_{xij}\left(z_j,t_k\right)\right)^2+\left(\sum_{i=1}^{N}V_{yij}\left(z_j,t_k\right)\right)^2+\left(\sum_{i=1}^{N}V_{zij}\left(z_j,t_k\right)\right)^2\right]/2, \quad (2)$$

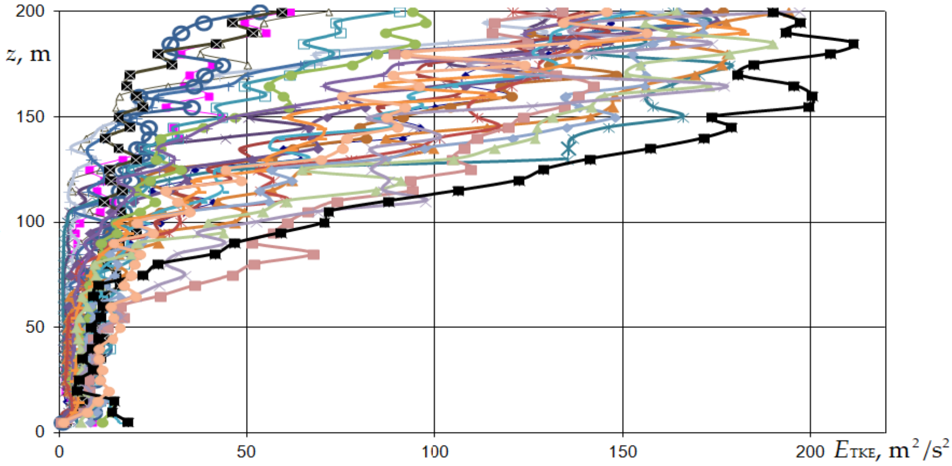
$$E_{\mathrm{TKE}}(z_j,t_k)=\left(\sigma_x^2(z_j,t_k)+\sigma_y^2(z_j,t_k)+\sigma_z^2(z_j,t_k)\right)/2=\frac{1}{N^2}$$
$$\times\left[\left(\sum_{i=1}^{N}V_{xij}\left(z_j,t_k\right)-\left\langle V_x\left(z_j,t_k\right)\right\rangle\right)^2+\sum_{i=1}^{N}\left(\left(V_{yij}(t_k)\right)-\left\langle V_y\left(z_j,t_k\right)\right\rangle\right)^2+\sum_{i=1}^{N}\left(\left(V_{zij}(t_k)\right)-\left\langle V_z\left(z_j,t_k\right)\right\rangle\right)^2\right]/2, \quad (3)$$

where $V_{mij}\left(z_j,t_k\right)$, $m = x, y, z$ are the wind velocity components measured with a minisodar in the jth range gate at altitude z_j in the kth series of minisodar measurements started at time t_k, $\left\langle V_m\left(z_j,t_k\right)\right\rangle$ are their 10-min averages, and σ_m^2 (z_j, t_k) are their variances.

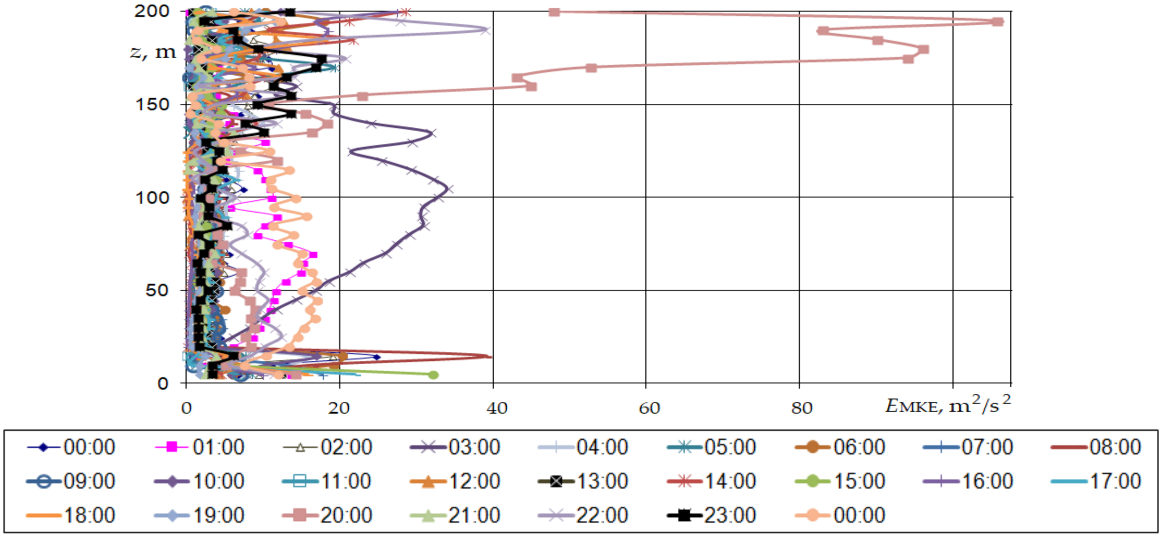
3. Results and discussion

We processed the results of measurements performed in the vicinity of Santa Clarita, California, USA, with an AV4000 minisodar from 12 till 17 September, 2006 [11]. The working frequency of the minisodar was 4900 Hz, its pulse duration was τ = 60 ms, and pulse repetition period was 4 s. Acoustic radiation was periodically transmitted in three directions – vertical and at elevation angles of 76° in two mutually orthogonal planes. The vertical profiles of three wind velocity components $V_{mij}\left(z_k\right)$, $m = x, y, z$ were measured in 43 range gates z_k with $\Delta z = 5$ m in the altitude range 5–200 m. The measurement site was relatively level, with no pronounced highs or lows, without high vegetation. The weather was dry, warm, and sunny. Measurement series from N profiles ($N = 150$, 300, and 450) were processed that provided from 10 to 30 min averaging of the results obtained.

Results of investigations of the spatiotemporal dynamics of the kinetic energy $E(z, t)$ and their diurnal hourly dynamics are presented below. A special attention is given to the turbulent kinetic energy component. Figure 1 shows the vertical profiles of the kinetic energy components from the results of processing of the minisodar data. It illustrates the diurnal hourly dynamics of the kinetic energy components on September 14. The start times t_k of 10-minute measurement series are indicated under the figure. Attention is drawn to a small spread of E_{TKE} values up to altitudes $z \approx 50$ m, and their largest spread from $E_{\mathrm{TKE\ min}}$ = 50 m²/s² at 09:00 to $E_{\mathrm{TKE\ max}}$ = 200 m²/s² at 23:00 at $z \approx 200$ m. From 10:00 till 12:00, the contribution of the kinetic energy of average motion in the lower 100-meter layer exceeded the contribution of the turbulent kinetic energy component, which was probably caused by the presence of wind shears in the corresponding vertical profiles of the horizontal wind velocity components. From the figure it is also seen that E_{MKE} increases in the morning from 05:00, reaches maximum values at 12:00, and then decreases till the midnight. The maximum value of the turbulent kinetic energy at the altitude z = 200 m was observed at 05:00, and the minimum one in the morning at 07:00, local time. The analogous behavior of the kinetic energy was also pointed out in [3] from measurements with a FAS64 sodar at three altitude ranges z = 20–50, 50–80, and 80–110 m. According to [3], the diurnal behavior of the turbulent kinetic energy was also characterized by the presence of minima and maxima. It is obvious that the time of their occurrence and their values depend on the meteorological conditions of observations, the presence and characteristics of cloudiness, and solar radiation.



a



b

Fig. 1. Diurnal hourly dynamics of the kinetic energy components on September, 14 with 10-minute averaging: *a* – turbulent kinetic energy E_{TKE} and *b* - kinetic energy of ordered motion E_{MKE} (associated with the average wind velocity).

During three days of continuous sodar measurements (on September 12, 14, and 15), the total kinetic energy changed from several ten to several hundred m^2/s^2, which is in agreement with the available literature data [3, 12]. From the figure it can also be seen that the turbulent kinetic energy increased with altitude *z*. In the near-surface layer to altitudes of 25–50 m, it weakly depends on *z*. Thus, on September 12, it changed from 10 to 90 m^2/s^2 at *z* = 25 m; on September 14 and 15, it remained practically unchanged to *z* = 50 m. From Fig. 1 it is also seen that the diurnal spread of the kinetic energy increases with *z*, and at an altitude of 200 m, E_{TKE} changes already from 70 to 200 m^2/s^2, that is, almost triples during the day. Analogous behavior of the turbulent kinetic energy was observed in [3, 12]. It should be noted that our analysis of the influence of the averaging period (10, 20, or 30 min) on the *E* values performed in [9] demonstrated that they were practically independent of the averaging time for these averaging periods. The same is true for the case under consideration. The general peculiarities retained for other averaging periods; therefore, we do not consider them here. Thus, based on the data presented above we can conclude that the kinetic energy in the surface layer to altitudes of 25-100 m weakly depends on the observation altitude *z* (which we explain by the presence of the mixing layer at these altitudes) and increases with further increase in *z*. The diurnal behavior of the radiative heating of the Earth's surface causes the presence of minima and maxima of the total kinetic energy, whose observation times depend on the local weather conditions.

4. Conclusions

Based on acoustic remote measurements of the diurnal dynamics of the three wind velocity components and their variances in the lower 200-meter layer of the atmosphere, the kinetic energy of the atmosphere reduced to unit mass has been estimated, with a particular emphasis on the turbulent kinetic energy component. For a 24-h period of continuous minisodar observations, the turbulent kinetic energy in the surface layer was very low to altitudes of ~50 m. With increase in altitude from 50 to 100 m, the turbulent kinetic energy quickly increased, and at altitudes exceeding 100 m, its fast growth was observed, with a maximum at altitudes of 150–200 m.

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