ON FEASIBILITY OF LIDAR WIND SOUNDING IN SOLVING THE PROBLEMS OF CLIMATO–ECOLOGICAL MONITORING OF LOCAL AREAS

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Results are discussed of the statistical estimates of the accuracy of lidar wind sounding by comparing the lidar and rawinsonde data. The data of lidar wind sounding are shown to be directly applicable to climatological studies of the wind regime in the atmospheric boundary layer, with no correction; however, they need mandatory correction for the systematic error in case of their use in real time, in particular to forecast the evolution of atmospheric pollution.

Deterioration of the environmental conditions in the territory of our country, particularly in the areas adjacent to large industrial centers, substantially affects the climate features of separate regions, formed under the impact of the industrial pollution upon the state of the atmosphere. That is why the development of an efficient system for climato–ecological monitoring of local areas becomes a vital necessity.

Among a broad spectrum of fundamental and applied studies of that problem, the estimate of the background (climatological) state of the atmosphere of local areas, influenced by anthropogenic factors, and forecast of the spread and evolution of pollutants occupy a highly important place. However, solution of these problems is impossible without systematic data on concentration of the pollutants and physical parameters of the atmosphere, particularly on the wind speed and direction, since they significantly affect the level of air pollution and its dynamics.

Routinely such dependence is estimated using the so–called equation of balance (transfer) of atmospheric pollutants, which for a given pollutant, following Refs. 1 and 2, can be written in a reduced form

$$\frac{\partial s_a}{\partial t} + u\frac{\partial s_a}{\partial x} + v\frac{\partial s_a}{\partial y} + w\frac{\partial s_a}{\partial z} + \frac{\partial w_a s_a}{\partial z} = k_1\,\Delta s_a + \frac{\partial k\, s_a}{\partial z} + \varepsilon_a, \quad (1)$$

where s_a is the volume concentration of pollutant a; u, v, and w are the wind components along the x, y, and z axes; w_a is the vertical velocity of pollutant ($w_a < 0$); k_1 and k are the coefficients of atmospheric eddy diffusion due to horizontal and vertical motion of particles, respectively; ε_a is the rate of formation (sources) or decomposition (sinks) of the pollutant in unit volume; and, $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ is the Laplacian operator.

Wind components (u, v, w) are known to vary in space and time, so a special system of equations of hydrothermodynamics is used to retrieve them in schemes of numerical forecasting (see, e.g., Ref. 3). In this case Eq. (1) will enter a prognostic model. For practical purposes, however, Eq. (1) is used separately to calculate (forecast) the concentration of pollutant s_a, and is solved after the problem of forecasting wind, or, alternatively, the data of real wind measurements are used. In so doing, most atmospheric pollutants of industrial origin are considered to spread upward in the atmosphere at altitudes up to 1.0–1.5 km, while horizontal components of their transport coincide with the wind velocity components u and v (see Ref. 2).

In addition, there is another important circumstance that makes the reliable rigorous solution of Eq. (1) difficult. Namely, in the calculations for small areas, when local model is used, horizontal grid steps are equal to several kilometers or even to hundreds of meters.

All things considered, the systematic measurements of the wind parameters in many points of the inspected territory are needed to retrieve all the necessary data about the wind parameters, and their vertical profiles in the atmospheric boundary layer (up to 1.0–1.5 km) must be estimated with high resolution. Meanwhile, it is well known that rawinsonde data, widely used to estimate the vertical profile of wind velocity, do not meet such requirements and cannot support reliable local forecast of transport and evolution of pollutants over local areas (see, e.g., Ref. 4). We believe the necessary information on the parameters of wind velocity may be retrieved from laser sounding of the atmosphere, since, according to Ref. 5, it provides for the estimates of atmospheric fields with exceptionally high temporal and spatial resolution.

The only drawback of the technique of laser sounding of the atmosphere is low accuracy of the data obtained, which substantially decreases as the distance from the source of optical radiation increases. Keeping that in mind, before applying the lidar wind velocity data to the problems of regional climate and ecological monitoring, we must evaluate possible error in the lidar wind velocity data in comparison with the standard rawinsonde data, which usually serve to solve these problems. This is particularly essential for estimating and forecasting the level of atmospheric pollution over local areas.

The aim of the present paper is to consider the statistical estimates of the accuracy of lidar wind velocity observations on the basis of their comparison to the routine rawinsonde observations with the use of the "Meteor" system.

Systematic lidar wind measurements performed at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences were used for this purpose (wind parameters were retrieved by the correlation method of signal processing[6]) in combination with the data of rawinsonde observations conducted synchronously in Tomsk (56 °N, 85 °E) from May 3 to June 6, 1990. These field tests included 40 wind profiles measured at altitudes of

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from 200 to 1200 m, 26 of them were measured synchronously. Since all the data of lidar wind sounding were averaged over a 200 m altitude ranges at the state of preliminary data processing, the values of zonal (u) and meridional (v) wind components, used to construct synchronous data series and to estimate statistically their accuracy, were taken at altitudes of 300, 600, 900, and 1100 m.

The accuracy of lidar measurements of wind was statistically estimated on the basis of two different methodological approaches. The first is as follows. Initially, the deviations are calculated of the zonal ($\Delta u = u_1 - u_2$) and meridional ($\Delta v = v_1 - v_2$) components of wind velocity measured with lidar (u_1 and v_1) from rawinsonde (u_2 and v_2) data. Next the following parameters were found from them:

1. The average error of lidar sensing

$$m_{xj} = \frac{1}{n_j} \sum_{i=1}^{n_j} \Delta x_{ij} , \tag{2}$$

where Δx_{ij} are deviations of the respective wind parameter (here i is the serial number of measurement taken at the jth altitude range), and n_j is the total number of synchronous measurements taken at the jth altitude range.

2. The standard (root–mean–square) error

$$\delta_{xj} = \left[\frac{1}{n_j - 1} \sum_{i=1}^{n_j} (\Delta x_{ij} - m_{xj})^2 \right]^{1/2} . \tag{3}$$

Since the parameter m_{xj} may be taken as the estimate of the systematic error in lidar measurements, the corresponding standard error will be determined by the expression

$$\delta'_{xj} = \left[\frac{1}{n_j - 1} \sum_{i=1}^{n_j} (\Delta x_{ij})^2 \right]^{1/2} . \tag{4}$$

It should be emphasized that there exists an important condition limiting the applicability of wind lidar, i.e., the standard error of lidar measurements δ_x should be less than the root–mean–square deviation of the meteorological value σ_x that characterizes its actual variability.

The second approach to the estimate of the performance of lidar wind sensing and feasibility of using the lidar data in climate models involved the significance test on discrepancies between the average values of the wind parameters and their variances, as retrieved from the two separate lidar and rawinsonde data samples. To estimate the significance or randomness of discrepancies between the average values, we used the t_s criterion, which was calculated via expression[7,8]

$$t_s = |\bar{x}_1 - \bar{x}_2| \,/\, \sqrt{\sigma_1^2/n_1 + \sigma_2^2/n_2} , \tag{5}$$

where $\bar{x}_1$ and $\bar{x}_2$ are the average values for the two samples being compared; σ_1^2 and σ_2^2 are their respective variances; and, n_1 and n_2 are the lengths of samples being compared. This criterion makes it possible to test the assumption that significant differences between the values x_1 and x_2 are absent, i.e., the hypothesis that

$$|t_s| < t_s(P, k) , \tag{6}$$

where $t_s(P, k)$ is the critical value of the function t_s [here P is the probability (in our case $P = 0.95$) and $k = n_1 + n_2 - 2$ is the number of degrees of freedom], defined by the Student distribution.[7]

To find whether variances retrieved from the wind lidar and rawinsonde data differ significantly or randomly from each other, we used the T_H criterion, which is given by expression[7,8]

$$T_H = \sigma_1^2/\sigma_2^2 . \tag{7}$$

Here σ_1^2 and σ_2^2 are the variances calculated from the two samples of data, with the larger of the two placed in the nominator. The critical value of the criterion $F_{1-P}(n_1, n_2)$ is taken at the significance level $q = 1 - P = 0.05$ and found from the tables of critical values of F, constructed by Fischer[7] for various combinations of the numbers of degrees of freedom n_1 and n_2. If the condition

$$T_H \le F_{1-P}(n_1, n_2) \tag{8}$$

is met, the hypothesis about the randomness of the discrepancy between the variances σ_1^2 and σ_2^2 will be true.

Since we suggested two different methodological approaches to the estimate of the accuracy characteristics of wind lidar, their results are discussed separately.

Table I lists average (m_x), root–mean–square (σ_x), and relative standard ($\Theta_x = \delta_x/\sigma_x$, %) errors in deviations of the zonal (u) and meridional (v) components of wind velocity, retrieved from lidar wind sounding, from the components obtained by rawinsondes. The same table lists corrected values of the root–mean–square (δ'_x) and relative standard (Θ') errors (excluding systematic errors).

One sees clearly from Table I that the average errors in deviations of lidar wind observations from rawinsonde wind data, obtained with the standard "Meteor" system, are altitude dependent. The largest amount of increase in the systematic error of wind lidar measurements m_x is shown by the zonal component of wind velocity u as the distance from the source of optical radiation increases. Therefore, the well–known dependence is fully proved again, according to which the accuracy of lidar sounding decreases as the distance to the sounded layer increases.

TABLE I. Average (m_x), root–mean–square (δ_x), and relative standard ($\Theta_x = \delta_x/\sigma_x$, in %) errors of deviations of the data of lidar wind observations from the rawinsonde data obtained with the help of the "Meteor" system.

H, km	m_u	δ_u	δ'_u	Θ_u	Q'_u	m_ν	δ_ν	δ'_ν	Θ_ν	Q'_ν
0.3	0.4	5.2	5.3	67	68	1.2	4.3	4.5	74	78
0.5	2.4	5.7	5.8	68	69	0.8	4.5	5.0	65	72
0.7	3.8	4.7	5.4	57	65	1.8	4.2	4.2	68	68
0.9	4.2	4.2	3.9	65	61	2.0	4.4	3.3	76	57
1.1	5.1	4.5	3.2	96	68	2.1	4.4	3.2	86	63

The analysis of actual and corrected values of δ_x shows that in both cases the root–mean–square errors in wind lidar measurements increase within the 0.3–0.5 km layer, and either decrease or remain almost without changes with altitude increasing further. We note that these errors decrease most noticeably when the data of lidar sounding are corrected for systematic error m_x .

As for the relative errors, it is seen from their analysis that in most cases the values of Θ_u and Θ_v do not exceed 65–70%, particularly when the systematic error is excluded. In other words, they remain less than the actual variability of the zonal (σ_u) and meridional (σ_v) components of wind velocity. This means that the condition $\delta_x < \sigma_x$ is satisfied, under which the lidar wind data are practically applicable. However, large relative errors in the data obtained from lidar wind sounding give no way of making a reliable conclusion on feasibility of their use in problems of regional climate monitoring.

For this reason we compare below the average (m_x) and root–mean–square deviations (σ_x), calculated separately for the zonal and meridional components of wind velocity from two separate samples of data of the lidar and rawinsonde observations.

Table II lists average (m_x) and root–mean–square deviations (σ_x) of the wind components u and v, retrieved from wind lidar and rawinsonde data. It also lists the calculated and critical values of the criteria t_s and T_H, used to estimate the significance or randomness of discrepancies between the data of lidar and rawinsonde observations.

The analysis of this table shows that lidar data overestimate the zonal component in absolute value and underestimate the meridional component as compared to rawinsonde data, since we have found that $|m_u^{(l)}| > |m_u^{(r)}|$ and $|m_v^{(l)}| < |m_v^{(r)}|$ in the 0.3–1.0 km altitude range. With altitude increasing, these discrepancies increase markedly, particularly for the parameter u. In addition, it is seen from the same table that conditions (6) and (8) are met at practically all altitudes within the considered atmospheric layer, independent of the component analyzed, since the calculated values of t_s and T_H at these altitudes remain below their critical values $t_s(P, k) = 2.02 - 2.05$ and $F_{1-P}(n_1, n_2) = 2.0 - 2.5$. Only at an altitude of 1.1 km the criterion t_s, calculated for the average values of zonal component of wind velocity, exceeds its critical level.

TABLE II. Results of comparison of the data of wind sensing obtained with the use of rawinsondes (r) and wind lidar (l) against the criteria of significance of deviation t_s and T_H.

H, km	$u^{(r)}$		$v^{(r)}$		$u^{(l)}$		$v^{(l)}$		u		v		$t_s(P, k)$	$F_{1-P}(n_1, n_2)$
	$m_u^{(r)}$	$\sigma_u^{(r)}$	$m_v^{(r)}$	$\sigma_v^{(r)}$	$m_u^{(l)}$	$\sigma_u^{(l)}$	$m_v^{(l)}$	$\sigma_v^{(l)}$	t_s	T_H	t_s	T_H		
0.3	1.8	7.8	– 2.7	5.8	2.2	8.2	– 1.5	6.8	0.17	1.1	0.63	1.3	2.015	2.0
0.5	1.1	8.4	– 3.9	6.9	3.5	8.2	– 3.1	7.0	0.96	1.1	0.37	1.0	2.016	2.0
0.7	0.4	8.2	– 5.3	6.2	4.2	8.0	– 3.5	6.6	1.57	1.0	0.94	1.1	2.019	2.1
0.9	0.5	6.4	– 5.9	5.8	4.7	7.2	– 3.3	5.9	1.85	1.3	1.33	1.1	2.032	2.3
1.1	0.3	4.7	– 6.8	5.1	5.4	5.9	– 4.7	5.8	2.54	1.5	1.04	1.3	2.050	2.5

All this points to the fact that the average values and the variances of the zonal and meridional components of wind velocity, obtained from two samples of observations (lidar and rawinsonde) differ insignificantly for the most part of the sensed 0.3–1.1 km layer. From the point of view of statistics this means that the discrepancies between the rawinsonde and lidar data are random and insignificant, so that the data of lidar wind sounding may be successfully used to obtain the climatic estimates of the wind regime in the atmospheric boundary layer.

Thus the statistical analysis of the accuracy characteristics of wind lidar based on comparing the lidar data with the data of rawinsonde sensing by the "Meteor" system, allows two important conclusions:

1. The systematic error in wind lidar data is insignificant at lower levels (0.3 and 0.5 km) and becomes much larger above, within the atmospheric boundary layer. Lidar measurements overestimate the zonal component of wind velocity and underestimate its meridional component.
2. Wind lidar data may be directly, with no correction at all, be used for climatological studies of the wind regime in the atmospheric boundary layer (at altitudes up to 1 km). However, they have to be corrected before using in problems of real–time estimate and forecast of the state of atmospheric pollution on local and regional scales.

We note in conclusion that further efforts of researchers investigating the problem of application of the lidar data should be aimed at:

– upgrading the technical characteristics of wind lidar (its potential, geometric structure, time of signal integration, etc.) and increasing the efficiency of correlation technique used to retrieve the parameters of wind in the lower atmosphere;

– conducting longer field tests of wind lidar in various physico–geographical regions and various seasons. This will not only provide for a more reliable assessment of lidar application to the problems of regional climato–ecological monitoring of the atmosphere, but also for the necessary calibration of this measurement means.

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