

GEOPHYSICS

DIFFERENCES IN WIND VELOCITY PROFILES IN THE BOUNDARY LAYER ABOVE URBAN AND RURAL AREAS

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Results of synchronous remote measurements of the wind velocity profiles in the atmospheric boundary layer above Moscow and in a rural area 45 km from Moscow are given. Continuous measurements were carried out for one month by Doppler acoustic sonars (sodars). Random and systematic differences in the vertical profiles of the wind velocity in the city atmosphere from the atmosphere in the rural area have been discovered at altitudes up to 100 m. Above 150 m, the wind velocity and direction do not differ very much at these two posts.

INTRODUCTION

Establishing the patterns of winds blowing over a city is important for planning the future location of industrial projects and settlements and for determining the possible wind loads on buildings and other objects. First-hand data on the velocity and direction of winds in the mixing layer are needed as input data for short-term forecasting of ground concentrations of pollutants via dispersion models. Various models have been developed that describe the distribution of pollutants in the city atmosphere (box models), models that directly employ the proportionality of the impurity concentration C to the “ventilation parameter” $(HV)^{-1}$, where H is the altitude of the mixing layer, and V is the average wind velocity in this layer [1]. The dependence of C on the wind velocity over Moscow was experimentally corroborated in [2, 3].

The data on the wind field over a city are usually limited to the data from ground weather stations located within the city limits and in the suburbs and also the data for aerological probing done far from the city center. The changes introduced by the city into the local structure of the atmospheric boundary layer can strongly influence the wind velocity field. Hence the need to study the degree of representability of the data from the city outskirts for the city atmosphere.

In many countries the wind field over cities has been studied by remote acoustic sensing via Doppler acoustic sonars (sodars) [4–6]. There are even city weather stations equipped with Doppler sodars for monitoring the wind field [7, 8]. In several cities, such as Rome [9] and Paris [10, 11], sodar networks have been used to synchronously measure the wind velocity within city limits and in the outskirts. However, such measurements have been scant and their results cannot be reliably generalized to other regions and cities.

This paper presents the results of analysis of synchronous remote measurements of the wind velocity profiles done in 1993 in the atmospheric boundary layer above Moscow and in the rural area 45 km from Moscow. A brief discussion of the preliminary results of these measurements has been published in [12].

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1. THE METHOD AND THE EXPERIMENTAL CONDITIONS

The physical principles of the acoustic sensing of a wind field and the parameters of a Latan-1 three-component Doppler monostatic sodar, two identical copies of which were used in the given experiment, are thoroughly discussed in [13]. Here we only note that the echo signal of a monostatic sodar is determined from the backscattering (at an angle of 180°) of acoustic waves on small-scale turbulent inhomogeneities of temperature. In the regions where the intensity of the temperature fluctuations is low (e.g., above the upper boundary of the surface inversion layer, where thermal stratification is close to neutral), sodar measurements of the wind velocity are impossible because of the small signal-to-noise ratio. This feature of remote measurements (also inherent in radars and lidars) limits the altitude range of comparisons of wind velocities. Since the inversion altitude in rural areas is much smaller than in the city [3].

One sensing post was located on the roof of the three-story building of the Obukhov Aerophysics Institute of the Russian Academy of Sciences (AI RAS) in the center of Moscow.

The second post was located on the grounds of the Zvenigorod Research Station (ZRS) of AI RAS in the rural area not far from the town of Zvenigorod, which is 45 km to the west from Moscow. The remoteness of the post was sufficient for the "trail" of the city's island of heat to have no effect, no matter what the direction of winds were, while it made it possible to ignore the differences in the synoptic conditions at the two posts.

Round-the-clock measurements at both posts began on October 14 and ended on November 5. The measurements of the vertical profiles of velocity V and direction φ of winds were done with a 40-min averaging time from the beginning of each hour, except for periods of strong precipitation and for technical reasons. The strong acoustic traffic noise in the center of Moscow in daytime often limited the altitude of reliable determination of the values of V and φ to 150–200 m, while the lower sensing level was limited by parasitic reflections from buildings. The sensing range at ZRS at night was limited by low-level inversion, above which the turbulent fluctuations needed for echo-signal formation were practically nil. Hence, to keep the sampling volume constant, at each post only four intervals out of the available sensing altitude range were chosen, intervals that most fully characterized the wind profile and the variation of the acoustic signal in the 24-hour cycle in the appearance and destruction of inversion layers and convective structures. The median altitudes of each interval amounted to 69, 98, 142, and 186 m, respectively. Thus, the values of the measured quantities were averaged over 30–40-m altitude intervals. For comparison we used synchronous observations in Moscow and at ZRS with sufficiently high signal-to-noise ratios for all selected altitudes.

The autumn period of observation was characterized by an insignificant 24-hour variation in the wind velocity and temperature and by weakly stable or weakly unstable thermal stratification. In that season, transient processes in the morning and evening hours have little effect on the measurements, while, for example, in summer the wind velocity profile undergoes strong transformations in the same hours. Hence, during the experiment the differences in the stratification types at the two posts were determined by the city's "heat island" rather than by the different location of the posts or by synoptic processes. Nevertheless, complete conformity in the stratification types (estimated by the shape of the sodar echo signals in the facsimile records) was observed only in 60–70% of the total observation time.

2. RESULTS OF COMPARISON OF THE WIND VELOCITIES IN MOSCOW AND THE RURAL REGION

Figure 1 shows examples of comparison of some wind velocity profiles measured synchronously at the two posts. In Fig. 1a the profiles resemble each other, differing at different altitudes by ± 1 m/s, while in Fig. 1b they differ strongly either in size or in slope. Such marked differences in profiles, exceeding 2–3 m/s, were observed in approximately 10% of all events and corresponded to periods when the echograms of the sodar signal also differed substantially. Apparently, these differences are related to local perturbations in the wind velocity and do not reflect the influence of the city, since they exist only for a short time and lead to a random spread in the data that are being compared.

Figure 2 presents the results of measurements of the wind velocity at all altitudes in Moscow, V_M , and at ZRS, V_Z , in the form of a correlation diagram. The correlation coefficient $R(V_M, V_Z) \equiv \frac{(V_M - \langle V_M \rangle)(V_Z - \langle V_Z \rangle)}{\sigma_{V_M} \sigma_{V_Z}} = 0.81$ is extremely large if one takes into account the distance between the posts and

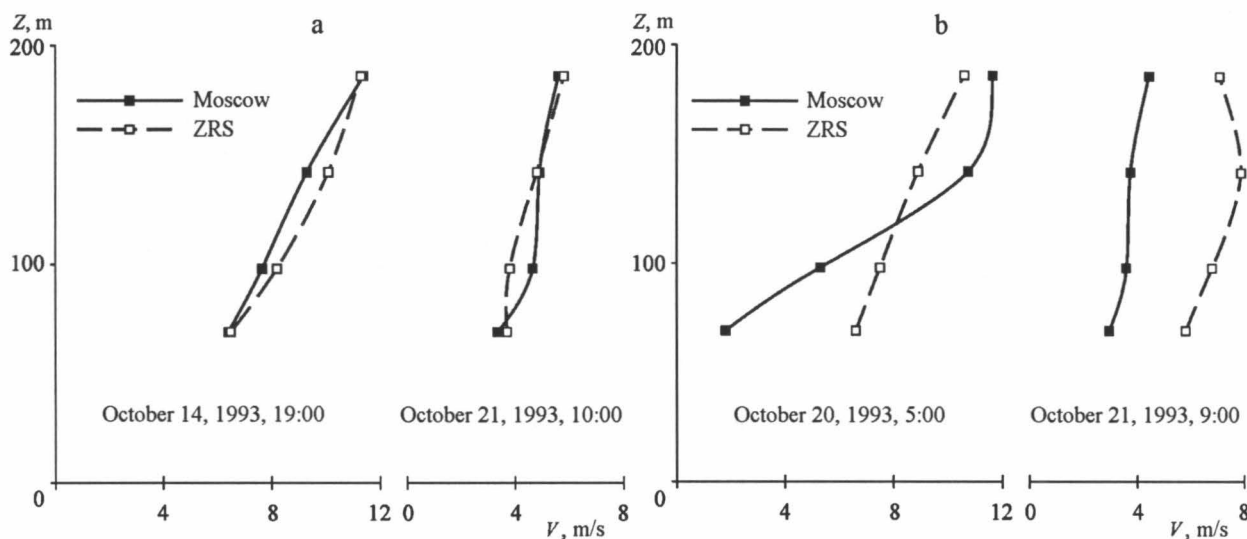


Fig. 1

Examples of synchronous vertical wind velocity profiles in the center of Moscow and at ZRS in (a) similar and (b) diverse conditions.

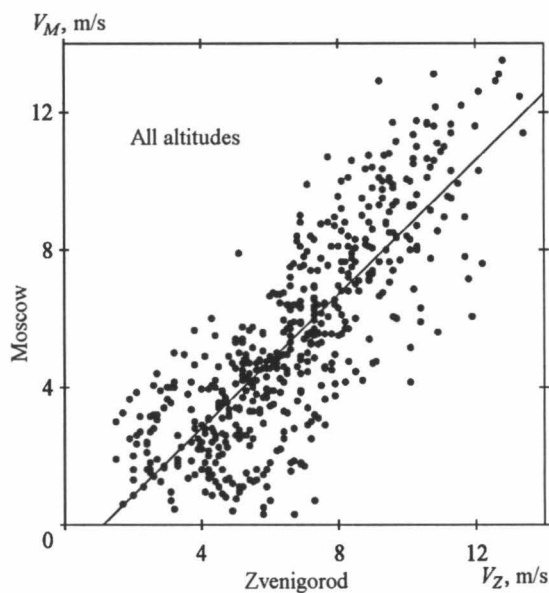


Fig. 2

Correlation diagram of observations of wind velocities in Moscow and at ZRS at all altitudes. The linear regression line is also shown.

the small range of the wind velocities (from 2 to 13 m/s). The diagram exhibits a systematic underestimation of the wind velocity by approximately 1 m/s in the center of Moscow compared to the rural area.

Figure 3 shows the correlation diagrams for each altitude separately, while the values of the linear regression $V_M = AV_X + B$ and the correlation coefficient R are listed in Table 1. The reader will recall that the measurement altitude h refers to the center of the volume over which the values of the wind velocity measured by the sodar are spatially averaged.

The diagrams and the data listed in Table 1 show that, as the altitude above the underlying surface increases, the difference in the wind velocities get smaller and, respectively, the correlation coefficient grows.

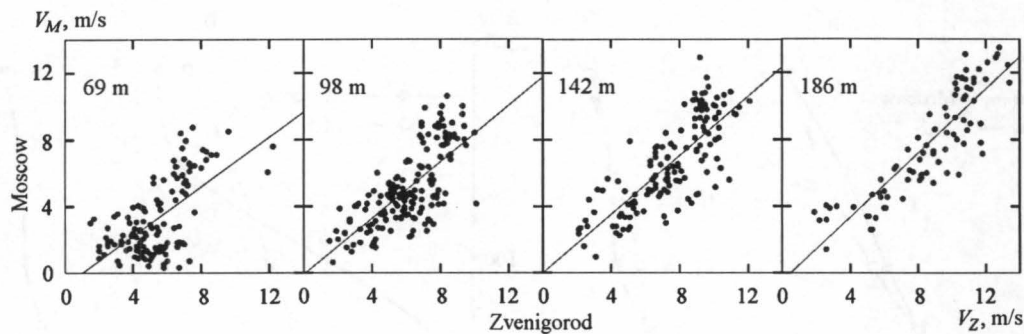


Fig. 3

Correlation diagrams of synchronously measured wind velocities in the center of Moscow and at ZRS in (a) similar and (b) diverse conditions.

Table 1

Coefficients of Linear Regression and Correlation

Measurement altitude h , m	69	98	142	186	All altitudes
A	0.75	0.85	0.88	0.96	0.97
B , m/s	-0.79	-0.11	-0.01	-0.50	-1.10
R	0.63	0.72	0.79	0.87	0.81

Since a characteristic feature of nighttime observations is a higher repetition rate of inversion, while in daytime the conditions are more favorable for convection (which is very small in the observation period), the observational data should be divided into blocks according to the time of day (and night).

From all simultaneous observations we selected the data gathered from 9:00 a.m. to 5:00 p.m. local time for the daytime sessions and from 9:00 p.m. to 5:00 a.m. for the nighttime sessions. The profiles belonging to each category were averaged irrespective of the value of the mean wind velocity. However, to guarantee homogeneity in statistical sampling, for the diagrams in Fig. 4 we used the data only for those cases where the wind velocity at both posts was measured at all four altitudes. As a result of such rejection, we were able to take into account only those conditions in which the thermal stratification within a certain altitude sensing range was the same at both posts.

Figure 4 shows that the averaged profiles taken at the two posts are very similar. The altitude dependence of the wind velocity, which is close to linear both at night and day, is characteristic of autumn with low convective activity. At nighttime the averaged profile of the wind velocity in the city has a somewhat larger slope, while during the day this slope is smaller than that of the rural slope. The differences in the average velocity are greater in the daytime than at night, but still they do not exceed 1.5 m/s.

The difference in the wind direction in the center of Moscow and in the outskirts is shown in Fig. 5 for the three upper levels of the sensing range. The wind directions at the lower level differ more strongly: approximately in 10% of the cases the differences in wind direction reach 30° (with 40-min averaging). The diagram exhibits a slight systematic shift of the "counterclockwise" direction (negative values), which is probably caused by a greater force of friction in the city, especially at small altitudes. On the whole, however, the diagram shows that the city has no noticeable effect on the wind direction at altitudes of 100–200 m.

3. DISCUSSION OF RESULTS

Analysis of the results of comparison has shown that in the lower part of the boundary layer the wind velocity above the city is, on the average, smaller than above the rural area. Such a decrease cannot be explained only by the presence of a city "heat island"; rather it can be attributed to a greater effective "roughness" area in the city, since in the autumn, when all measurements were made, the heating of the city by solar radiation and internal heat sources is moderate.

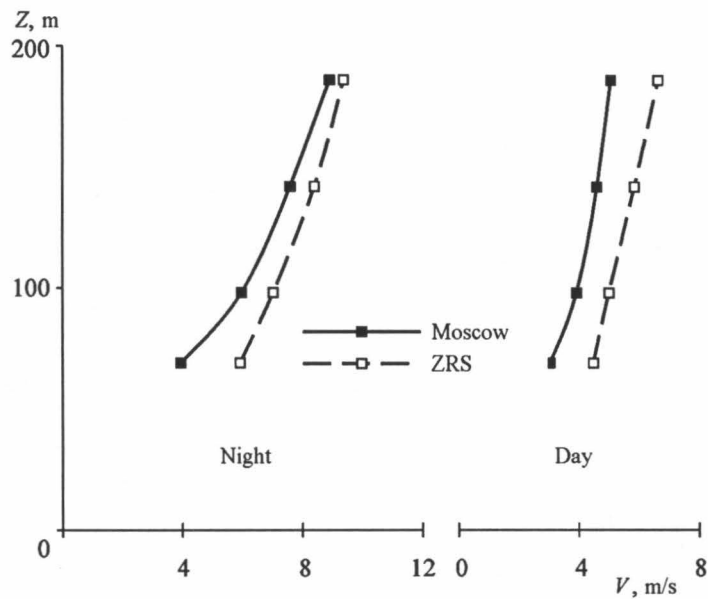


Fig. 4

Day and night wind velocity profiles averaged over the entire observation period.

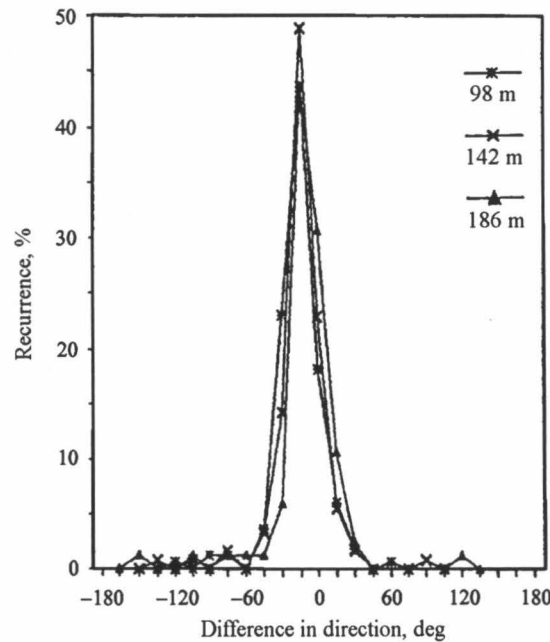


Fig. 5

The difference in wind direction in Moscow and at ZRS, $\Delta\varphi = \varphi_M - \varphi_Z$, averaged over all measurements.

Most observations (about 90%) exhibit a stable dependence of the wind velocity difference between city and outskirts. The relatively rare cases when the shapes of the wind velocity profiles at the two posts differed substantially were probably caused by local perturbations of the wind velocity, and their formation can hardly be explained by the effect of the city. However, the presence of such perturbations indicates the usefulness of sodar monitoring of the wind velocity within the city limits in order to monitor the potentially dangerous meteorological situations and to gather information for short-term forecasts.

The following differences in the velocity profiles have been established: a change in the slope of the profile in the 24-hour cycle, a faster decrease in the wind velocity at altitudes below 100 m within the city limits, and a larger dispersion of the difference in the wind velocity over the city and over the rural area at low altitudes. On the whole, these patterns agree with the data of [14], which to our knowledge is the only publication comparing the wind velocities in the boundary layer above Moscow and those far from the megapolis. However, the differences established in [14] were based on measurements done atop the Ostankino TV tower and the Obninsk (a town in the Kaluga region) tower and cannot be fully identified with the effect of the city due to the large distance between the observation posts.

According to our measurements, the wind velocity in Moscow is on the average 1 m/s lower than that in the outskirts of Moscow at the same altitudes above the underlying surface. This conclusion does not work for small altitudes comparable to the height of buildings. As repeatedly noted (e. g., see review [15]), at small altitudes the wind field in the city undergoes more spatial variations due to the effect of city "canyons" and turbulent eddies around high buildings. The large dispersion of the differences in the wind velocity at lower sensing altitudes (Fig. 4) corroborates this fact and suggests that the prospects of generalizing the differences to altitudes up to 100 m (for example, on the basis of the data gathered on moderately high meteorological towers) are slim. It is for this reason, too, that meteorologists often use not the data on surface winds but the data on what is known as geostrophic wind, determined by the pressure field. Thus, in cities sodar observations are almost the source of rapid-response monitoring of ageostrophic deviations of the wind velocity that appear in cyclogenesis and in the passage of wind fronts.

CONCLUSION

The use of acoustic remote sensing has made it possible to carry out synchronous measurements of wind velocity profiles above the center of Moscow and in an adjoining rural area. Earlier such comparisons were not done for Moscow, and it is difficult to imagine that other methods would work. Only simultaneous measurements at several points provide a pattern of the spatial variations of the wind field, a pattern determined by urban development and the effect of the city's "heat island." This problem, which is being solved for many big cities in the world, is still of high priority for Moscow.

Our results show that in autumn the wind field in the lower part of the boundary layer is fairly homogeneous. This conclusion is important for organizing the monitoring of that meteorological conditions that affect the buildup and local transport of pollution.

We note that the data obtained in the three weeks when the observations took place cannot serve as a basis for drawing final conclusions. They can only illustrate the possible situation, show how the data of real measurements in the center of a big city may differ from the results of observation in the nearest locations, and be the first part of a long program of measuring the wind field in the atmospheric boundary layer above Moscow. Many more measurement in other seasons are needed if we want to arrive at reliable conclusions.

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