THERMAL STRUCTURE OF THE ATMOSPHERIC BOUNDARY LAYER OVER MOSCOW

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Results of complex experiments on thermal structure of the boundary layer over Moscow performed by direct and remote methods are presented. Temperature profiles have been measured by sensors located on Ostankino TV tower and by low–level radar sondes located in the Central Aerological Observatory (Dolgoprudnyi town). Remote sensing has been carried out in Moscow and in Zvenigorod using three acoustic locators (sodars). Stratification type has been determined from facsimile recordings of sodar echos. Comparison of the data obtained simultaneously by different methods has been made; inhomogeneity of the temperature stratification of the lower atmosphere layer over Moscow has been estimated; periodical repetition of its main types during summer has been investigated. Comparison of the data obtained by simultaneous acoustic sounding at three points demonstrates influence of the big city on thermal structure of the atmospheric boundary layer.

1. INTRODUCTION

Knowledge of thermal stratification of the atmospheric boundary layer is of great importance for pollution meteorology. It determines the altitude of mixing layer and rate of turbulent diffusion of anthropogenic admixtures. The atmospheric boundary layer over big cities exhibit a number of common features such as, for instance, "island of heat".[1] However, there are also certain specific features related to climate, landscape and the building density. Therefore, special investigation is needed in order to estimate pollution potential in a city.

Such measurements have been many times carried out in Moscow region at high–altitude monitoring stations in Ostankino and Obninsk as well as using radiosondes in Dolgoprudnyi.[2–5] However, these data are insufficient for description of atmospheric boundary layer over a big city with the area of 1000 km^2.

Acoustic sounding of the atmosphere is a promising method of studying the atmospheric boundary layer.[6–13] Facsimile recording of echos from a monostatic sodar enables one to determine the type of thermal stratification, i.e. to monitor the convective conditions, surface and elevated inversions, neutral stratification. We used the procedure of interpretation of echos basically developed at the Institute of Atmospheric Physics (IAP) of the Russian Academy of Sciences, see, for example, Refs. 12 and 13.

During a 3 years period continuous round–the–clock sodar observations have been carried out at Moscow State University (MSU) Meteorological Observatory (south–west sector of the city). In addition, monthly cycles have been periodically conducted in the city center (on the roof of the building of the Institute of Atmospheric Physics) and at Zvenigorod IAP scientific station (45 km far from Moscow). Comparison of the results of synchronous sounding at different points presented in Refs. 11 and 13 showed that the type of thermal stratification is basically the same within the city area (with the exception for transition periods during morning and evening hours). At the same time, analogous comparison of the data obtained at MSU with the temperature profiles measured along Ostankino TV tower showed significant deviations between them. This can be explained either by actual differences in the structure of the boundary layer in Ostankino and at MSU (these points are 14 km apart) or by the errors in determination of stratification by one of the methods. In order to solve this problem as well as to perform detailed investigation of atmospheric boundary layer a combined experimental study has been carried out. Detailed description of this experiment and some preliminary results obtained were presented in Ref. 14. In this paper, the above–mentioned data are complemented with the measurement data from Zvenigorod and by data on comparison of sodar data obtained at three points.

2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

Experiments were carried out from June 24 till July 25, 1991 and included the following measurements:

– round–the–clock facsimile recording of echos from three sodars located near Ostankino TV tower, in the center of the city and near Zvenigorod;

– measurements of temperature profile and wind velocity on the TV tower according to special program;

– measurements of temperature and wind velocity at three levels of a 4 m high meteorological mast mounted 80 m far from the TV tower;

– measurements of temperature profile and wind velocity by low–level and standard radiosondes launched at Central Aerological Observatory in Dolgoprudnyi (13 km to the north from Ostankino).

Besides, measurements of temperature and wind velocity during the same time conducted on a 300 m high meteorological tower located in Obninsk (108 km to the south from Ostankino) were used for analysis of the results obtained. Below, brief description of the experimental equipment and measurement technique is presented.

A sodar of EKhO–1 type transported from MSU (see Ref. 5) was installed 400 m far from the TV tower, on

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the roof of a 10 m high building. Its main parameters are as follows: f = 1666 Hz, Δh = 13 m, P = 75 W, and ΔH = 50–800 m. Here f is the carrier frequency, Δh is the spatial resolution, P is the electrical power consumed by the emitter, ΔH is the altitude range of operation. Two identical sodars LATAN–1 (see Refs. 10 and 12) were used on the roof of IAP building and at Zvenigorod IAP scientific station. They have the following parameters: f = 2000 Hz, Δh = 17 m, P = 100 W, and ΔH = 30–850 m (for sodar located on the roof of IAP building ΔH = 30–560 m). The type of stratification was determined from facsimile records made every hour using a procedure described in Refs. 12 and 13. The records were stored in a memory for further statistical processing of data.

High–altitude automatic system ASMIB–G for meteorological measurements located on the TV tower has been described in Refs. 16 and 17. During experiments the temperature was measured at 2, 85, 128, 201, 253, 385, and 503 m levels, whereas the wind velocity was measured at 15, 128, 201, and 253 m levels. From June 24 till June 30 the measurements were carried out in three hours and since July 1 they were hourly. The type of stratification was determined in two different ways, i.e., based on equitemperature lapse $\gamma = \Delta t / \Delta z$ and on the dry adiabatic lapse $\gamma_\theta = \Delta\theta/\Delta z$. These two variants were used in order to obtain better agreement with sodar data. The cases of $\gamma \le \gamma_a$ ($\gamma_\theta \le 0$), where $\gamma_a = -0.98°/100$ m were considered as unstable stratification. If $\gamma > 0$ and $\gamma > \gamma_a + 0.1°/100$ m, these cases were considered as inversion or weakly stable stratification. According to measurements on the TV tower the stratification was considered to be neutral if at least any three of six γ values determined by temperature difference at two adjacent levels were equal to zero. The stratification was considered to be neutral as well if at least four γ values were lower than $\gamma = 0.1°/100$ m. The same criterion though with a corresponding shift was also used for lapse of potential temperature θ. We determined the type of stratification in such a complicated way because of a strong vertical oscillations of the temperature profile occurred during measurements. This fact will be discussed below.

Measurements of temperature with Assmahn psychrometers at 1 and 4 m altitudes and of wind velocity v with Fuss anemometers at 2 m altitude were carried out on a 4 m high mast simultaneously with the measurements conducted on TV tower. Based on these data the analog of parameter of stability was calculated from the equation $B_2 = 0.067\ (t_4 - t_1)/v_2^2$. This parameter enables us to estimate the degree of stability of the surface layer in terms of Pasquill classes according to recommendations of Byzova.[18]

During the experiment, 77 radiosondes were launched of which 58 sondes were standard and 19 were the low level ones. The resolution of temperature measurements along the vertical axes was 100 and 35 m, respectively. This resolution is comparable to the difference of altitudes for sensors located on the TV tower. Thirty three sondes were launched at night, six ones during daytime, and three sondes were launched in the evening. The type of stratification was determined using both the equitemperature and dry adiabatic lapses.

It should be noted that meteorological conditions in Moscow varied significantly during the experiment. However, on the whole, with exception for the first week with its very hot weather, the values of main meteorological parameters were typical for the middle summer.

3. PRELIMINARY ANALYSIS OF DATA OBTAINED WITH AN ASMIB–G SYSTEM

During the period of 1990–1991 we have carried out a comparison of data obtained with a sodar at MSU with the measurements conducted on the TV tower in order to study the spatial inhomogeneity of the atmospheric boundary layer. In doing so, we relied on numerous data reported by foreign scientists on agreement between the sodar and lapse estimations of the stratification type (see for instance a review in Ref. 19). In addition, the comparison of data obtained on Ostankino TV tower with facsimile records of an AIROVIRONMENT sodar echos. This sodar had been operated near the tower in 1981 before ASMIB–G system was developed. Despite the lack of statistical data in this paper,[20] good agreement between sodar image of a surface inversion with the temperature profiles has been demonstrated, though in one particular case.

However, our data showed that during one year and a half the surface inversions were observed simultaneously at MSU and in Ostankino 3.57 times more rarely than at both points separately. Moreover, the periodic repetition of the types of stratification was different too. Thus from temperature profiles measured in Ostankino surface inversion occurred during 23.6% of the total period of experiments and elevated inversions were observed during 60.1% of the total period of experiments, whereas from sodar observations these values are 40.9% and 17.1%, respectively.

First of all, we analyzed the possibility of misinterpretation of sodar data related to the blind zone of sodar and to the reflection of the signal from nearby buildings. Separate comparison of sodar data with temperature profiles measured in Ostankino that was made without regard for data obtained with two lowest sensors (i.e. for the layer lying higher than 128 m where there is no effect of reflected signal) did not lead to better agreement between the occurrences of surface inversions. At the same time, strong fluctuating behavior of vertical temperature profiles measured on the tower as well as localization of elevated inversions in the range of altitudes between 128 and 253 m was discovered. Figure 1*a* presents temperature profiles measured at different time as averaged over the set of observational data in October 1990. The characteristic bend can be easily seen at these altitudes.

Time averaged temperature profiles for the total period of experiment, including those obtained on the TV tower, high–altitude mast in Obninsk, and with radiosondes are presented in Fig. 1*b*. Measurements made in Ostankino and Obninsk were carried out at 3^{00} and 15^{00}. In Dolgoprudnyi there were performed radiosonde launches at 2^{30} and 14^{30} (only standard sondes in this case). One can see that sharply varying profiles obtained on the TV tower again occurred during daytime and at night at the altitudes between 150 and 300 m. At the same time, both radiosondes data and high–altitude tower measurements in Obninsk demonstrate usual smooth temperature profile. Specific features of Dolgoprudnyi (in fact, it is a suburb of Moscow) as compared to the far more distant Obninsk are in the higher temperature near the ground and lower inversion at night. The latter is indicative of the presence of the urban "island of heat".[1] During daytime stratification is more unstable in Dolgoprudnyi than in Obninsk. This fact confirms the known regularities in urban climatology.

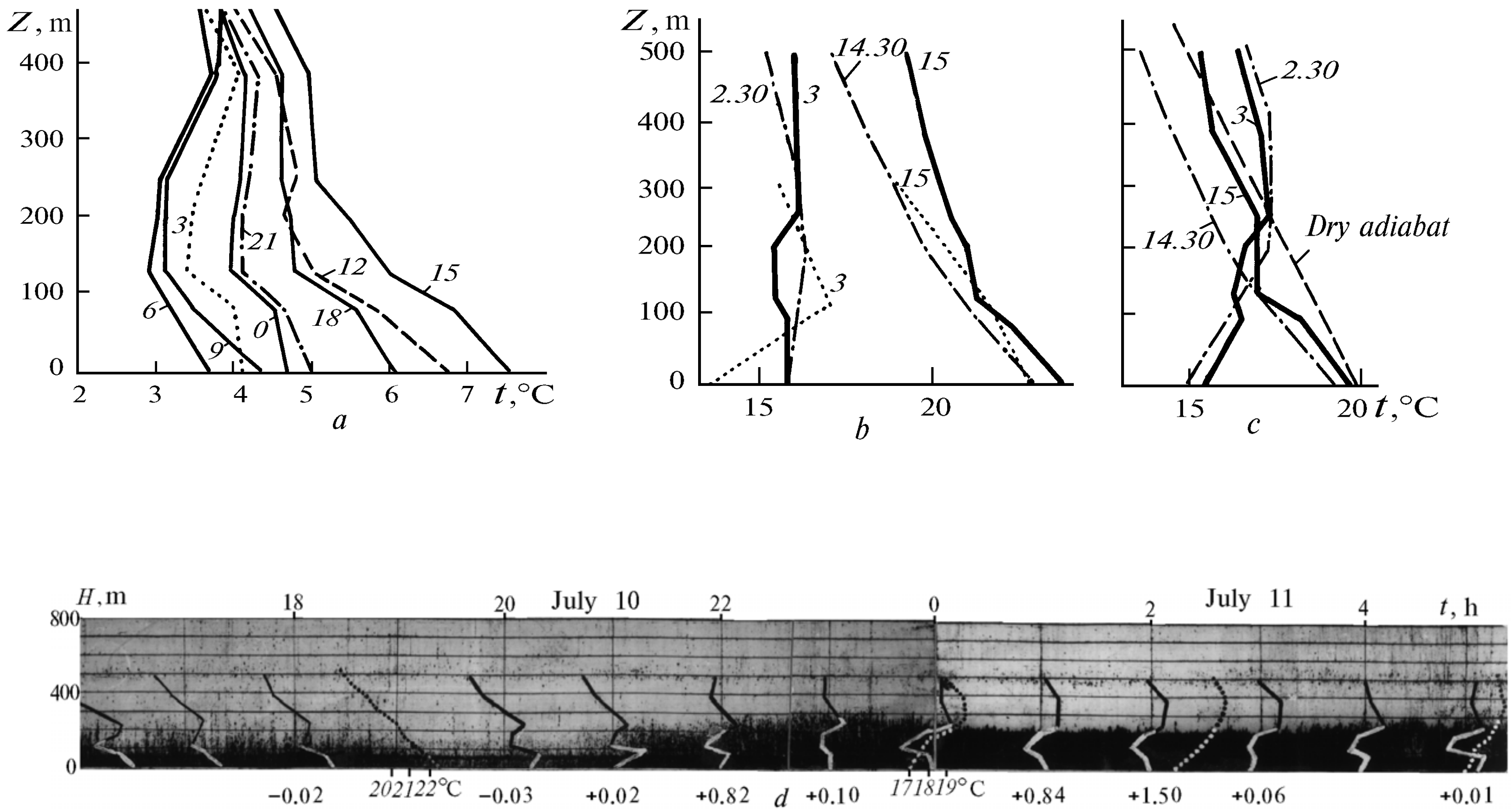

FIG. 1. Vertical temperature profiles obtained from data: a) measurements made on the TV tower time averaged for October 1990, b) measurements made at three points averaged over the whole period of experiment, c) measurement, made on the TV tower and with radiosondes averaged over time for periods of intense temperature advection, d) measurements made on the TV tower and with radiosondes plotted over the facsimile recordings of sodar echos in Ostankino, July, 10–11, 1991 (blackened layer at the recording carried out at night corresponds to the temperature inversion region, B_2 values are presented at the bottom). The moment of the measurements are indicated in hours near the curves (a, b, and c) solid lines correspond to the measurements made in Ostankino; dashed–dotted lines present measurements made in Dolgoprudny; dotted lines present data obtained in Obninsk (b and c). In Fig. 1d solid lines correspond to the measurements made using sensors installed on the TV the tower, dotted lines present data radiosondes in Dolgoprudny.

It should be noted that specific features of the profiles obtained in Ostankino were noticed earlier. Possible explanation of this phenomenon is considered in more details in Ref. 14. What is worth noting here is the hypothesis of Ferapontova[21] on the thermal influence of aerosol layer that could result in the constantly observed elevated inversion at the altitudes between 150 and 300 m over Moscow, independent of a season and time.

It is well known that intense invasions of air masses take place (i.e. when the air masses change – this is attributed to the large horizontal temperature gradients) washing out of aerosol from the lower atmosphere occurs. Take–off and bubble–like lift of the overheated urban air under the influence of forces of buoyancy shortly after passing of a front of cool air makes an additional atmospheric cleaning effect which occurs due to cold advection. We studied temperature profiles obtained on the TV tower and by radiosondes taking into account this phenomenon. In doing so, we calculated the values of geostrophic component of temperature advection using AT_{850} maps and 10 cases of intense invasions during the period of experiment were picked out. Figure 1*c* presents nighttime and daytime temperature profiles averaged over time for the periods of intense advection. As is seen from Fig. 1*c* the bending in the Ostankino profiles remains at the same altitudes. This fact contradicts the hypothesis proposed in Ref. 21. It should be noted that Ostankino daytime temperature lapses deviate from the adiabatic behavior. Data obtained by sondes are typical for temperature variation with altitude irrespective of time. Thus, before a direct comparison of sodar data with measurement data by ASMIB–G system we could conclude that use the latter data for determination of temperature lapse was doubtful.

4. COMPARISON OF THE TYPES OF STRATIFICATION DETERMINED IN DIFFERENT WAYS

Figure 1*d* shows a typical portion of a facsimile echogram of an EKhO–1 sodar together with the ASMIB–G and radiosondes temperature profiles plotted over it. The stability parameter B_2 in the surface layer is shown at the bottom by numbers. The echogram provides a reliable identification of the convective stratification that takes place before 19^{00}, that is close to neutral between 19^{00} and 20^{30}–21^{00}. Ground inversion occurred during the subsequent hours is also easily detectable from echograms. It agrees well with radiosondes data and B_2 values. At the same time, profiles obtained on the TV tower demonstrate constant occurring elevated inversion, absence of surface inversion and even layers with unstable stratification during the period between midnight and 2^{00} a.m. Horizontal line at 500 m altitude is the signal caused by reflection from the TV tower.

The coefficient of correlation between γ values in the lower part of the atmospheric boundary layer and the degree of thermal stability are represented in Table I as obtained from simultaneous independent measurements during the whole period of the experiment. To calculate these factors, the sodar data and lapse data in 4 m layer were divided in 7 Pasquill stability classes. The possibility of such a presentation of sodar data was proven in Ref. 22.

As one can see from this table, the correlation of the data obtained on the TV tower with the data obtained by all other methods is too low. More accurate matching in time of the sodar measurements with the measurements conducted on the TV tower did not essentially improve the correlation for a set of 578 hours volume. Sodar data agree well both with the low level sounding results and lapse measurements in the lowest layer. It should be noted that discrepancy between sodar data and results obtained by two other methods occurred mainly early in the morning when take off of the radiative inversion and onset of convection flow near the ground are masked on the facsimile recording due to the sodar blind zone and spurious reflections.

TABLE I. Coefficients of correlation R between γ values and types of stratification (n is the bulk of sampling).

Sodar	TV tower 2–85 m	TV tower 2–128 m	n, hours
	0.38/0.40*	0.43/0.47*	578
	Low–level radiosonde	TV tower (2–128 m)	n, hours
TV tower(2–128 m)	0.42	1.00	19
Sodar	0.77	0.57	19
	Mast	TV–tower (2–128 m)	n, hours
TV tower(2–128 m)	0.48	1.00	51
Sodar	0.84	0.60	51

* The numerator contains the R values obtained in the determination of stratification according to the sodar data in the hour interval, and the denominator contains the R values obtained in the last ten minutes of each hour (i.e., in the moment of the measurement t on the TV tower).

The frequency of occurrence of different types of stratification as it follows from sodar data and measurements made with a ASMIB–G system is presented in Table II for a 578 hours long set of data. In addition, data obtained by radiosondes are presented for a set of 74 hours long. Elevated inversion and stable layers were observed on the TV tower 5 times more frequently than with a sodar. On the contrary, surface inversion was observed more frequently on echograms. Convection in the absence of blocking layers was detected with sodars 3.5 times more frequently than with an ASMIB–G system. The same regularities are revealed though from smaller bulk of experimental data obtained with a sodar and an ASMIB–G system. Data obtained by radiosondes agree better with sodar information than with those obtained on the TV tower. Anomalously high frequency of occurrence of elevated inversions recorded on the TV tower is confirmed neither by sodar nor by radiosonde data. It should be noted that absolute values of the frequency of occurrence of an unstable stratification in the set of 74 hours length are somewhat overestimated because of relatively higher number of radiosonde launches in the middle of the day.

TABLE II. Frequency of occurrence of stratification types (n is the bulk of sampling).

Types	1	2	3	4	5	n, hours
Sodar	30.1	5.1	12.3	35.5	17.0	578
ASMIB–G, $\Delta T/\Delta z$	2.9	18.7	63.8	10.4	4.2	<
ASMIB–G, $\Delta h/\Delta z$	10.9	42.0	45.5	–	1.6	<
Sodar	33.8	8.1	8.1	44.6	5.4	74
ASMIB–G, $\Delta T/\Delta z$	4.0	23.0	54.1	12.2	6.7	<
Radiosondes	29.7	–	13.5	54.1	2.7	<

Notes: Simultaneous measurements with ASMIB–G on the TV tower, sodar in Ostankino, and radiosonde in Dolgoprudnyii Solitary surface inversions (1), both surface and elevated inversions (2), elevated inversions in the absence of surface ones (3), convective conditions (4), and stratification close to neutral one.

Table III presents the time in hours during which surface inversion and surface dry steady layer were observed by a sodar and an ASMIB–G system simultaneously. Comparison was performed separately for the whole period of experiments and for the period characterized by anticyclone type of weather (from June 24 till July 8). The number of inversions simultaneously detected by a sodar and an ASMIB–G was only one third (40% for anticyclonic weather) of the total number detected with both these methods. When data obtained with an ASMIB–G system were reduced to the dry adiabatic lapse the agreement of these data with the sodar ones occurred again in less than a half of the total number of cases. It is true both for the whole period of experiments and for the first two weeks, as well.

The whole period of observations of elevated inversions detected using both these methods was 507 hours (the majority of data were obtained on the TV tower). At the altitudes higher than 503 m the elevated inversions recorded on the echograms were observed only during 3 hours. Coincidence was considered as taking place in all cases when the lower boundary of elevated inversion detected with a sodar was at least not higher than the upper boundary of the bend in temperature profile (and *vice versa*). However, even for such a "liberal" approach the elevated inversions were observed simultaneously by two methods during 58 h. Thus, only two thirds of the layers detected with a sodar (86 h) and only 12% of those observed with an ASMIB–G system (479 h) can be considered as simultaneous ones. Therefore, data on inversions obtained at the same point by two different methods strongly contradict each other.

TABLE III. Comparison of the number of events when surface inversions and dry stable layers were recorded with a sodar and an ASMIB–G system during the experiment.

Recorded with	Whole period, 578 hours (24 June – 25 July)		Period with anticyclone weather, 232 hours (24 June – 8 July)	
	$\Delta T/\Delta z$	$\Delta\theta/\Delta z$	$\Delta T/\Delta z$	$\Delta\theta/\Delta z$
Only sodar	129 (22.3)	42 (7.3)	45 (19.4)	15 (6.4)
Only ASMIB–G	52(9.0)	147 (25.4)	25 (10.8)	65 (28.0)
Both instruments	76 (13.1)	163 (28.2)	46 (19.8)	76 (32.8)
Absence according to data from both instruments	321 (55.6)	226 (39.1)	116 (50.0)	76 (32.8)

Notes. Figures show the number of hours, the percent of the general time of observation is given in brackets.

Figure 2 presents schematic comparison of the results obtained simultaneously by three methods at all points, where the experiments were carried out (with the addition of sodar sounding in the center of Moscow and near Zvenigorod). Black sectors in the circles located near arrows combining different sources of information in pairs show in per cent how often the presence or the absence of surface inversion was observed by both these methods simultaneously. One can see that sodar data obtained in Ostankino agree substantially better with other sources than with measurements data acquired on the TV tower. Sodar and TV tower sources being located only 400 m apart show coincidence only in two cases of three accurate to sign of γ value. At the same time, coincidence for other pairs of sources is as high as 85–90% of cases though they are located much farther from each other. This fact shows that spatial inhomogeneity of the thermal stratification of the atmosphere over Moscow is significantly lower than the error in stratification measurements with an ASMIB–G system. It should be noted that analogous comparison of data obtained with radiosondes at the Central Aerological Observatory and on Ostankino TV tower, that was made 20 years ago demonstrated good agreement in 90% cases.[2] This fact together with the results of comparison made more than 10 years ago[20] shows high quality of the measurements carried out on the TV tower that time.

Analysis of the profiles of wind velocity was not assumed to be presented in this paper. This part of the experimental results is summarized in Ref. 14.

5. ESTIMATION OF SPATIAL INHOMOGENEITY OF THERMAL STRUCTURE OF THE ATMOSPHERIC BOUNDARY LAYER OVER MOSCOW BASED ON SODAR DATA

Data presented in Fig. 2 show rather high homogeneity of thermal stratification of the atmospheric boundary layer over Moscow and their suburbs. If measurements made on Ostankino TV tower are excluded the remaining 8 pair combinations of three sodars, radiosondes and measurements made in Obninsk demonstrate coincidence in the sign of γ in 87–88% cases, on the average. However, this comparison was carried out for a shorter (72 hours) series of measurements. Moreover, this series includes small information about transitional periods of a day. Comparison of data obtained from three sodars for the whole period of observation is more reliable. Coincidence of the number of cases when of the presence or absence of surface inversions observed at the Institute of Atmospheric Physics and in Ostankino makes 88.1% cases for 464 hours long operation of both sodars; Zvenigorod and Ostankino data agree in 84.5% cases for 387 hours long operation; Institute of Atmospheric Physics and Zvenigorod data coincide in 83.6% cases for 373 hours long operation. Thus, according to our experiments one can conclude that in summer the stratification of the lower atmosphere is similar over the distances 10^4–10^5 meters in 85–90% cases. The above–stated results demonstrate correctness of the sodar estimations of thermal stratification of the atmospheric boundary layer. Therefore, it is possible to analyze in detail the spatial inhomogeneity of the atmospheric boundary layer based on the data obtained with three sodars, which, in contrast to sondes and tower measurements, provide a possibility of acquiring such an information day and night.

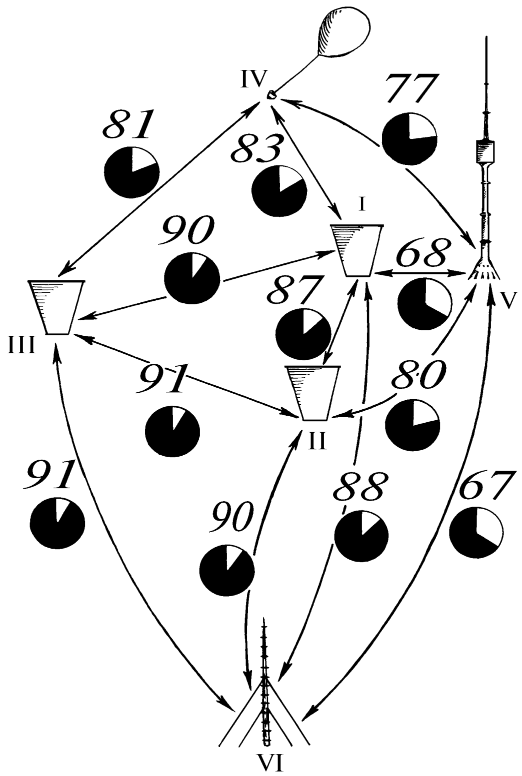

FIG. 2. Spatial inhomogeneity of the temperature stratification in the lower atmospheric layer over Moscow region. Frequency of coincidence of the data obtained at different sites is indicated as black sectors. The data from the following sites are presented: sodar located in Ostankino (I), sodar located in the center of Moscow (II), sodar located in Zvenigorod (III), radiosondes in Dolgoprudnyii (IV), measurements made in Ostankino on the TV tower (V), and measurements made in Obninsk on high mast (VI).

Figure 3 presents data on pair comparisons of the types of stratification simultaneously detected with sodars located at different points, namely, in the center of Moscow, in Ostankino (peripheral region of the city), and near Zvenigorod (countryside near Moscow). Agreement between observations of surface inversions as well as convective conditions is observed in 70–80% cases and for a shortest of two series of observations of this type this number is 80–90% and even higher. It should be pointed out that surface inversions are observed more seldom whereas unstabilities are observed more frequently in the city center than in its periphery. Agreement in detection of elevated inversions is less evident. There is also no regularity of their occurrence at different points. They were observed more frequently at the Institute of Atmospheric Physics and in Zvenigorod than in Ostankino. Neutral and weakly stable stratification that occur in summer, usually only in the evening hours, are observed simultaneously at two different points relatively more seldom than other atmospheric situations. At the same time, this type of stratification is approximately symmetric for any pair of measurement series and therefore does not reveal any influence of the city.

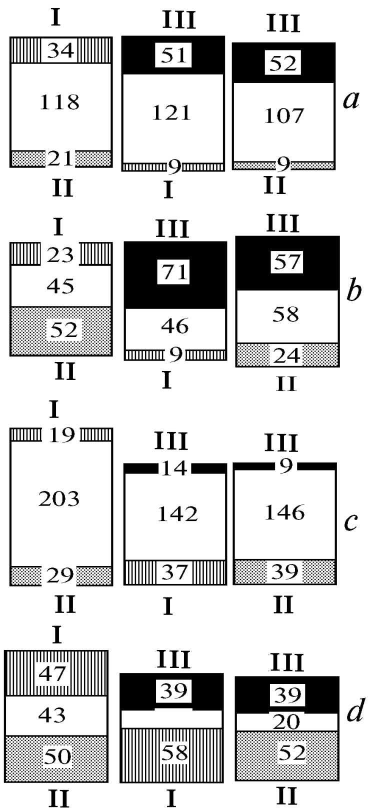

FIG. 3. Diagrams of comparison of the types of stratification determined by two sodars simultaneously during the period of experiment. Periods of time (in hours) when certain type of stratification was observed only at one point or only at another one or at both points simultaneously are indicated by figures. Surface inversions (a), elevated inversions (b), convection conditions (c), and neutral and weakly stable stratification (d). Only in Ostankino (I), only at the Institute of Atmospheric Physics (center of the city) (II), only in Zvenigorod (III), white field represents the cases when observation was made simultaneously.

Circular diagrams presented in Fig. 4 are constructed based on 361 hours long simultaneous operation of there sodars. They demonstrate more clearly relative frequency of observation of different types of stratification at every point of sodar location. These data agree with the conclusions drawn from the results presented in Fig. 3. The overall frequency of occurrence of surface inversion (horizontal shading) was 29.8% at the Institute of Atmospheric Physics, 32.4% in Ostankino, and 42% in Zvenigorod. On the contrary, this characteristic for the convection (sector with dots) increases from 41% in Zvenigorod to 50.4% in the center of the city. Elevated inversions (three black sectors, one in each stratification of the surface layer) were observed in Ostankino more seldom than at other points. Neutral and weakly stable situations (white sector) were observed somewhat more frequently in the city. Probably, this fact can be explained by slower formation of surface inversion in the city in the evening.

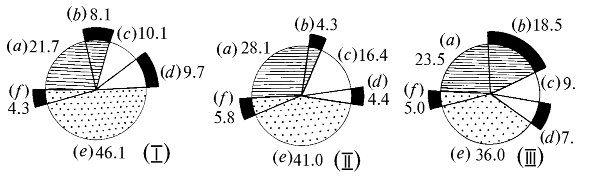

FIG. 4. Frequency of occurrence (in per cent) of the types of temperature stratification in hours of simultaneous observation by all the three sodars: surface inversions in absence of elevated ones (a), elevated inversions over surface ones (b), neutral and weakly stable stratifications in absence of elevated inversions (c), elevated inversions over neutral and weakly stable stratifications (d), convection in absence of elevated inversions (e), convection blocked under elevated inversions (f). Center of Moscow (Institute of Atmospheric Physics) I, Ostankino II, Zvenigorod III.

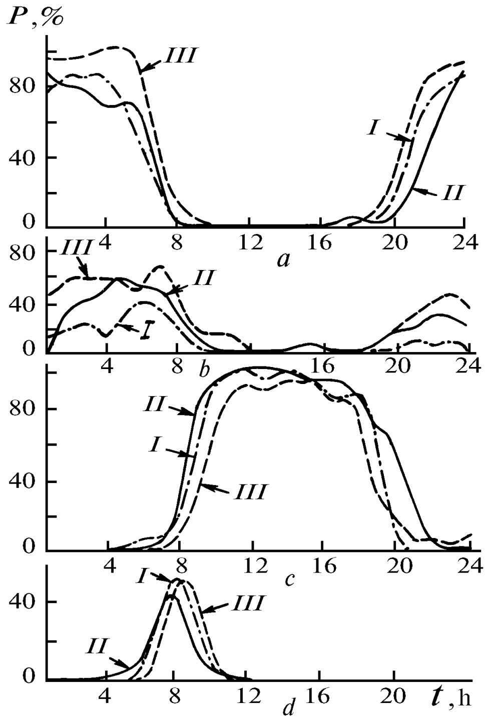

FIG. 5. Diurnal behavior of the frequency of occurrence of the types of stratification in hours of simultaneous observation with the three sodars: surface inversions (a), elevated inversions over neutral and weakly stable stratification (b), convection in absence of elevated inversions (c), and convection under elevated inversions (d). Ostankino (I), IPA (Moscow center) (II), and Zvenigorod (III).

It should be noted that simultaneous observation of the types of stratification by two sodars in summer 1990 (see Ref. 11) showed significantly larger differences in the surface inversions and convection observed at the Institute of Atmospheric Physics and Moscow State University than in observations carried out a year later at the Institute of Atmospheric Physics and in Ostankino. Since both points (Moscow State University and Ostankino) are approximately equidistant from the center of Moscow, this fact suggests an idea on possible a symmetrical shape of the "island of heat". Together with air circulation over the city it is somewhat displaced to the northern part of Moscow. Such a displacement is probably caused by specific features of the city building because its density is not equal in different districts. To verify this assumption, it is advisable to undertake such an investigation based on a larger number of sounding points.

In order to carry out detailed analysis of the characteristic features of differences in stratification observed at three points we have plotted daily mean frequencies of occurrence. As seen from Fig. 5, the surface inversion in the city occurs 1–2 hours later in the evening, and this stratification is less stable during the whole night as compared to the situation in the suburbs (Fig. 5*a*). On the contrary, convection is stable at noon at all three points. City circulation related to the "island of heat" affects convection mainly in the transition periods and results in somewhat longer duration of the convective conditions in the center (Fig. 5*c*). In the morning take off of the surface inversion layer and the following development of unstable stratification occurs about 1 hour earlier in the center than in the suburbs (Fig. 5*d*). Mainly the difference in the frequencies of occurrence of convection observed at different points is formed in the evening hours. Thus damping of the ascending convective fluxes occurred about 2 hours later at the Institute of Atmospheric Physics compared to this event in Zvenigorod. Elevated inversions in neutral or stable stratifications in the lower layer are observed mainly in the transition time (Fig. 5*b*) when the strongest influence of the "island of heat" takes place. That is why these types of stratification are monitored simultaneously at different points very seldom.

6. CONCLUSION

The combined experiment, discussed above, proved the correctness of sodar estimations of thermal stratification of the atmospheric boundary layer and showed good prospects for using sodars both for statistical investigation of the structure of the atmospheric boundary layer over the city and for its operative evaluation.

Based on the results of the experiment the quantitive estimation of horizontal inhomogeneity of thermal structure of the surface layer was obtained for the first time. On the average, the type of stratification is the same during 85–90% of the total daytime for distances 10 to 100 km accurate to the sign of γ. As to comparison of the types of stratification the surface inversions and convective conditions are observed simultaneously at different points in 70–80% of cases.

Specific features of the influence of a big city on the thermal structure of the atmospheric boundary layer have been revealed. In particular, a decrease of the frequency of occurrence of surface inversions and its increase for the convective conditions was observed for the direction from periphery to the center of the city. Main differences in thermal structure of the atmospheric boundary layer (including elevated inversions) observed in the different districts of the city and in the suburbs mainly took place in the transition time.

Analysis of the temperature profiles measured with an ASMIB–G system located on Ostankino TV tower and comparison of these profiles with the data obtained using other methods showed that there were systematic errors in measurements on the TV tower which resulted in distortions of the actual vertical temperature profiles.

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