AIRBORNE ECOLOGICAL SOUNDING OF THE ATMOSPHERE

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The paper is the continuation of our earlier papers on the analysis of aircraft–laboratories intended for monitoring of the environment and is devoted to the methods of application of aircraft–laboratories as integrated complexes beginning with the transboundary transfer and ending with local monitoring. The paper presents examples of application of the OPTIK–E AN–30 aircraft–laboratory to sounding of air at regional and urban scales, of generalization of the data to the territory of the former USSR, and of the data on the emission of individual large sources. A conclusion has been made about the most effective application of the aircraft–laboratories to regional monitoring including the elements of monitoring at transboundary and local scales.

Our previous papers[1,2] described the instrumental complexes of aircraft–laboratories used for measuring the air quality in different geophysical regions including that exposed to the anthropogenic activity. This paper is devoted to the analysis of application of the aircraft–laboratory, as an integrated complex, to ecological monitoring of the state of the air basin.

At first glance it was logical to assume that the more complicated ecological situation in many countries could result in the intensive application of the aircraft–laboratories to the determination of the spatiotemporal distribution and the dynamics of pollution taking into account the advantages of the airborne method.[2] However, there are a few papers devoted to the application of the aircraft–laboratories to ecological monitoring of the air basin of polluted regions.

One of the most comprehensive ecological observations of the areas with the help of the aircraft–laboratories was carried out by the US Environmental Protection Agency and the Canadian Department of Atmospheric Air Protection.[3] During this experiment the inventory was made of emissions from point and spread sources of atmospheric pollution in the region that includes the southern part of the Ontario and Manitoba provinces, the south–east part of the Saskatchewan province, and the Eastern States of America. The NCAR and NASA aircraft–laboratories[2] were used in this experiment.

In 1983 the Commission of the European Communities and the Department of Environment of France carried out the investigation of air pollution in the Fost–de–Baire region using the rented aircraft with a lidar.[4]

The first Soviet system of automated monitoring of the gaseous pollution of air near the heat–and–power station (HPS) was elaborated at the Zaporozhskaya state regional power station. The complete cycle of observation of its industrial zone had been carried out earlier. The atmospheric parameters in the layer below 300 m were measured by sensors mounted on a mast. Measurements above 300 m were carried out by aircrafts and helicopters.[5]

Blumenthal et al.[6] reported on the experiment aimed at following the artificial gaseous clouds in order to study the peculiarities of their diffusion. The Cessna–206 aircraft–laboratory was used for measurements.[2]

Rather successful experiments on estimating the distribution of some pollutants were carried out in the Munich region[7,8] with the help of the Falcon–E aircraft–laboratory.

The information about sounding of the vertical distribution of air pollution in the region of Japan Islands with the help of the Cessna–404 and B–737 aircraft–laboratories was given in Refs. 9 and 10.

The main and common demerit of the above–enumerated experiments was the lack of scientifically validated scheme of flights for sounding of air pollution as well as their incompleteness. The flight was designed intuitively by investigators.

Only the methods of determination of the transboundary transfer of pollutants with the help of the aircraft–laboratories are the exception. These methods were thoroughly developed at the E.K. Fedorov Institute of Applied Geophysics.[11]

TRANSBOUNDARY TRANSFER OF POLLUTION

The long–range transfer of pollutants was studied according to the Convention on Transboundary Air Transfer.[12] According to the commitments of the former USSR, the aircraft–laboratory that carried out measurements over the fixed flight lines along the western boundary of the state at regular intervals throughout the year, was created at the Institute of Applied Geophysics. The length of the flight route was 100–150 km and was chosen reasoning from the requirements of model calculation of fluxes.

The atmosphere was sounded at altitudes up to 2.5–5 km at 300–600 m intervals.

The procedure[13] based on the assumption that the conditions of transfer were relatively uniform on the section of the boundary with the length L_j was used to calculate the transboundary fluxes of pollution. For the amount of substance transferred in the time t, one can write down the expression

$$Q_{ij} = P_{ij} L_j \Pi_{ij} t ,$$

where the substance flux transferred through the unit section of the boundary is determined by the expression

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$$\Pi=\frac{1}{J}\int_0^J\int_0^h C(x,\ y)\ U(y)\cos\alpha\ \mathrm{d}y\ \mathrm{d}x=\sum \overline{C}(y_i)\ U(y_i)\cos\alpha_i\ \Delta y_i.$$

Here J is the length of the flight route passing parallel to the boundary or near it, h is the altitude of the upper boundary of the layer of transfer, $C(x, y)$ is the substance concentration, $\overline{C}(y_i)$ is the mean concentration at the altitude $y_i \pm \Delta y_i/2$, $U(y)$ is the wind velocity, $\alpha = \alpha_i$ is the angle between the wind direction and the normal to the boundary, the subscript i specifies the direction of the transfer (for example, $i = 1$ denotes the transfer into the region and $i = 2$ denotes the transfer out of the region), P_{ij} is the probability of the transfer in the given direction, and Π_{ij} is the mean flux transferred through the unit section of the boundary.

For the net fluxes one can write

$$Q_{1j} = Q_j^{\mathrm{in}} + d_{ij}\, Q_j^{\mathrm{out}} + Q_j^{\mathrm{nat}}\ ;$$

$$Q_{2j} = d_{ij}\, Q_j^{\mathrm{in}} + Q_j^{\mathrm{out}} + d_{2j}^{\mathrm{nat}}\, Q_j^{\mathrm{nat}}\ ,$$

where Q_j^{out}, Q_j^{in}, and Q_j^{nat} are the fluxes determined by the emissions from the sources located outside the boundary, inside the region, and from the natural sources, respectively, and d_{ij} are the relative fractions of fluxes which return through the boundary due to the circulation of the atmosphere

$$Q_{1j}^{\mathrm{nat}} = \left|Q_j^{\mathrm{nat}}\right|^{\mathrm{in}} + d_{1j}\ \left|Q_j^{\mathrm{nat}}\right|^{\mathrm{out}}\ ,$$

$$Q_{2j}^{\mathrm{nat}} = \left|Q_j^{\mathrm{nat}}\right|^{\mathrm{out}} + d_{2j}\ \left|Q_j^{\mathrm{nat}}\right|^{\mathrm{in}}\ .$$

To estimate the pollution of the atmosphere, one should know the values of Q_j^{out} and Q_j^{in}, and to estimate the sedimentation, one should know the budget of the fluxes

$$\Delta Q_i^{\mathrm{in}} = Q_j^{\mathrm{in}} - d_{2j}\, Q_j^{\mathrm{in}} = Q_j^{\mathrm{in}}(1 - d_{2j})\ ,$$

$$\Delta Q_i^{\mathrm{out}} = Q_j^{\mathrm{out}} - d_{1j}\, Q_j^{\mathrm{out}} = Q_j^{\mathrm{out}}(1 - d_{1j})\ .$$

The transfer through the entire boundary is found by summing up the values of Q_j^{out}, Q_j^{in}, $\Delta Q_j^{\mathrm{out}}$, ΔQ_j^{in}, and Q_j^{nat} over $j = 1, \ldots, n$.

It is assumed that $P_{ij} = P_i$ and $d_{ij} = d_i$ for the period $t = 1$ year for all sections of the boundary. The values of P_i estimated from the data on the transfer trajectories and wind velocity distribution[13] were $P_1 \approx 0.63$ and $P_2 \approx 0.37$ with an error of no more than 20%. The values of d_0 estimated by the trajectory method and from the calculations of the East–European Meteorological Synthesis Center (MSC) were $d_1 = 0.15$ and $d_2 = 0.1$ with an error of 25–30%.[12]

In addition to the aforementioned routine method, the climatic method of estimation of the fluxes of harmful substances from the empirical data[12] was developed in the former DDR. In this case it is not required to know the emission of pollutants and the coefficients of physical–chemical transformations. The equation

$$\Pi = \int_0^H C(z)\ U(z)\ \mathrm{d}z$$

provides the basis for the calculation of the mass rate Π. Here H is the altitude of the upper boundary of the layer in which the pollutant spreads, $C(z)$ is the concentration of pollutant at the altitude z, and $U(z)$ is the horizontal wind velocity at the altitude z.

In calculations it is assumed that all harmful substances spread mainly in the atmospheric layer below 1500 m, and the region of spreading of harmful substances is bounded by the maximum height of the mixing layer. To determine $U(z)$, the data of aerological sounding at altitudes of 300, 600, 900, 1200, and 1500 m are used.

The mass rate is calculated individually for each 300 m layer so that the total daily mass rate in the layer of spreading is given by the equation

$$\Pi = 300 \int_1^H \overline{C}(\Delta z)_i\ \overline{U}(\Delta z)_i\ \mathrm{d}z\ ,$$

where i is the layer number, $\overline{C}(\Delta z)_i$ is the mean concentration in the ith layer with the thickness Δz_i, $\overline{U}(\Delta z)_i$ is the average daily wind velocity in the ith layer.

The wind velocity components are determined in the Cartesian coordinate system with the X axis directed eastward and the Y axis directed northward by the formulas

$$\overline{U}_{xi} = -\ \overline{U}_i \sin\varphi_i\ ,$$

$$\overline{U}_{yi} = -\ \overline{U}_i \cos\varphi_i\ ,$$

where the angle φ_i specifies the wind direction in the ith layer.

The components of the mass flux in the X and Y directions are obtained in the form

$$\Pi_x = 300 \int_1^n \overline{C}_i\ \overline{V}_{xi}\ \mathrm{d}z\ ,$$

$$\Pi_y = 300 \int_1^n \overline{C}_i\ \overline{V}_{yi}\ \mathrm{d}z\ .$$

Here the flux is directed toward the east for $\Pi_x > 0$, and toward the north for $\Pi_y > 0$.

The total flux in the layer of spreading is equal to

$$\Pi = \sqrt{\Pi_x^2 + \Pi_y^2}\ ,$$

and the principal direction of spreading of the total mass flux is specified by the angle

$$\varphi = \frac{3}{2}\,\pi - \arctan\frac{\Pi_y}{\Pi_x}\ .$$

We will not dwell on the results obtained as part of the above–described projects. They have already been published in detail. After disintegration of the USSR, the new aspects appeared in the statement of the problem of

studying the transboundary transfer of pollution. Let us pay attention to them. To this end let us address to the map of the distribution of the suspended substances over the territory of the USSR averaged over a period between 1981 and 1991 (Fig. 1). This map was made at the Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences with the help of the OPTIK–E AN–30 aircraft–laboratory.[1] Data of vertical sounding of the atmosphere in different geographical regions were used to make the map. The data were time averaged. The vertical extention of the layer of measurements changed from 5 to 8 km. However, the data were averaged over 0–3 km layer in which the overwhelming bulk of aerosol was concentrated. The profiles obtained in the regions exposed to the effect of the industrial centers were excluded from data processing.

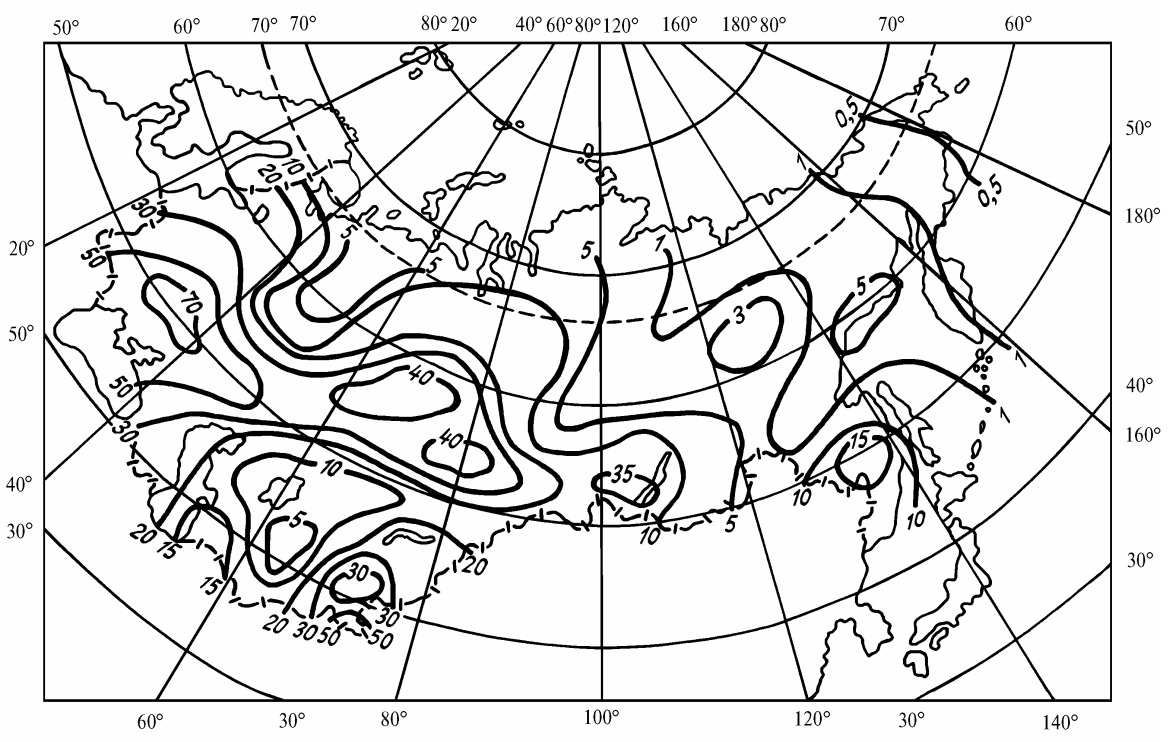

FIG. 1. Distribution of aerosol number density ($\bar{N} = \frac{1}{H}\int_0^H N(h)_i\,\mathrm{d}h$) *over the territory of the former USSR.*

It can be seen from Fig. 1 that several zones of enhanced content of suspended substances are pronounced in the mixing layer over the territory under consideration. The principal zone is located over the western regions of the European part of the USSR and is caused by addition of the enhanced background concentrations of the aerosol being transferred from Western Europe and from the emissions of the Donetsk–Dnepropetrovsk industrial zone taking into account the west–east direction of aerosol transfer.

The effect of this zone spreads to the south regions of Eastern Siberia. True, the strengthening effect of the Ural industrial zone is added as well as the effect of the industrial objects located in the Northern Kazakhstan and in the south of Western Siberia. This effect is manifested itself by the appearance of two additional regional zones of the enhanced aerosol concentration. The background concentration of suspended particles in the region exposed to the effect of the Irkutsk industrial zone is somewhat lower. One more quite clearly pronounced zone of enhanced aerosol concentration ($N > 50$ cm^{-3}) is over the territory of the Central Asiatic Republics. Its appearance can be explained by the stagnation of air in the mountain valleys where the industrial enterprises are concentrated.

In spite of the fact that we have excluded all the profiles measured over the "caps" of the industrial cities from data processing, Fig. 1 shows that now the anthropogenic activity determines the regional background of pollution.

REGIONAL MONITORING OF AIR POLLUTION

Taking into account the fact that state boundaries have no effect on the air pollution, the problem arises of the estimate of the amount of air pollution caused by the emission of the industrial enterprises located in the republics of the former USSR as well as in the regions and territories which have got independence.

These problems can be solved by regional monitoring with the help of the aircraft–laboratories.

Let us consider possible implementation of regional monitoring by the example of the territory of Western Siberia including several regions. When the idea of regional monitoring matured, the appropriate project was pioneered by academician V.E. Zuev. The scheme of this project is shown in Fig. 2.

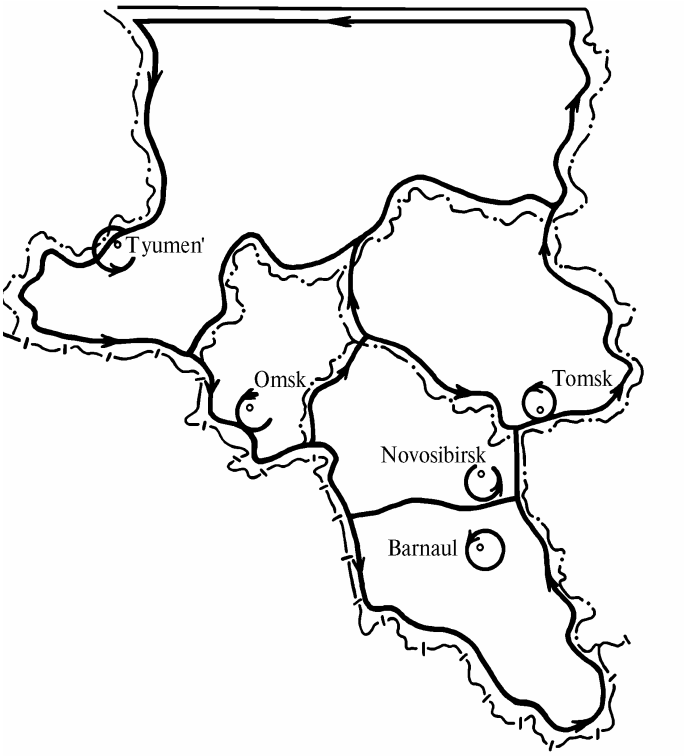

FIG. 2. Scheme of regional monitoring of Western Siberia (on a 1:16 M *scale). —·— stands for boundaries of areas and territories, —/— shows state boundary, and → is flight lines.*

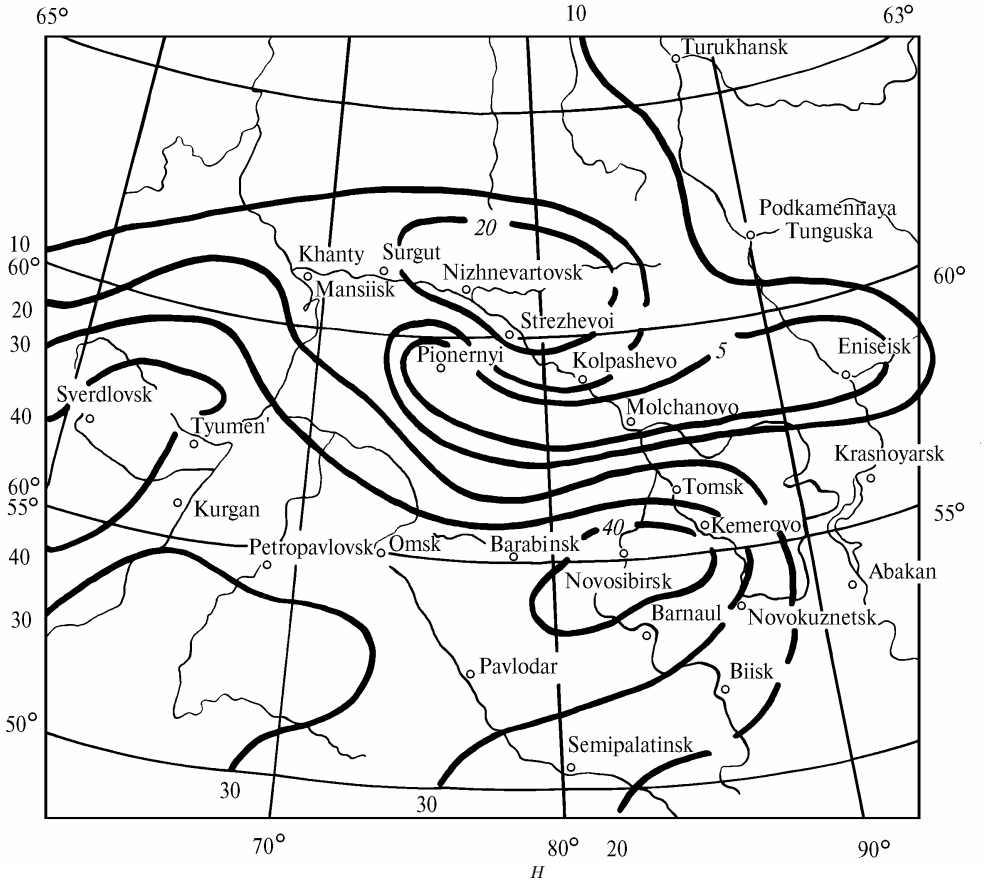

FIG. 3. Aerosol number density $(\bar{N} = \frac{1}{H}\int_0^H N(h)_i \, \mathrm{d}h)$ *over Western Siberia.*

The objective of this project is the study of the patterns of influx and transfer of pollutants in the territory of Western Siberia and of spatial distribution of aerosol and gaseous atmospheric pollution.

To implement this project, the regular flights should be conducted within the 100–8000 m altitude range along the boundary of the territory to be monitored and around large industrial centers. After the flights one should obtain the maps of air pollution distribution, investigate the transfer, transformation, and generation of pollutants in the region, record the substance budget, estimate the regional and interregional pollution budgets, study the principal transfer directions and the areals of spreading of pollution from large sources, and determine the ratio of "own" and "foreign" pollutants in the region under consideration.

The content and scheme of the project were approved at the Meeting of the heads of Environmental Protection Bodies of Siberia and Far East (February, 1991). Joint financing of this project by all regions was contemplated. However, the embodiment of this project was put off for indefinite period due to financial problems.

Nevertheless, a part of such a work was carried out. It was based on the previous investigations performed at the Institute of Atmospheric Optics and on the periodic flights of the OPTIK–E AN–30 aircraft–laboratory in 1991.

The obtained distribution of suspended substances over the above–indicated region is shown in Fig. 3. The conditions of mapping were the same as in Fig. 1.

It can be seen from Fig. 3 that in addition to two zones indicated above (Ural zone and the south of Western Siberia), one more zone appears in the Nizhnevartovsk–Strezhevoi region. As the analysis shows, it is engendered by the substance emissions due to combustion of the accompanying gases in the plumes of oil occurrences. In addition, there is a narrow zone of a relatively low aerosol concentration ($N = 50$ cm^{-3}) in the center of Western Siberia. This zone lies between two pollution sources located on the north and on the south of the region.

In our opinion, the mean distribution shown in Fig. 3 underlines the need for regional monitoring of this territory. If even the mean background aerosol field reveals the climatically sighificant peculiarities, the change of the air circulation in various seasons will result in spread of pollutants from the selected zones in any directions including those where the background is not yet enhanced.

Another question is appropriate, whether the high levels of air pollution in Kemerovo result from the influx of air with very high background content of pollutants with subsequent addition of the emissions of local industrial enterprises. Judging from Fig. 3, we may ask the administration of other cities the same question.

A start of regional monitoring of his own and adjacent territories has been made by the Buryat Council of Ministers. Such an approach to this problem contrasts with the passive position of administrative bodies of Western Siberia.

In commission of the Buryat Council of Ministers, the Institute of Atmospheric Optics and the Ecological–Geochemical Surveying Party of the Production Association "Buryatgeologiya" carried out the aerosol and gas survey of Buryat and Baikal Lake in 1991. The purpose of this work was determination of the regional transfer of the air pollutants and estimation of possible pollution of Baikal Lake through the atmospheric channel. The scheme of flights over this region is shown in Fig. 4. As a rule, two flights were executed along each route at two altitudes of 400 and 900 m over the local relief.

The results of operation by the scheme shown in Fig. 4 allowed the Production Association "Buryatgeologiya" to map the distribution of more than 50 air pollutants on a 1:1 M scale. Because of large bulk of data, we will not present the entire data array.

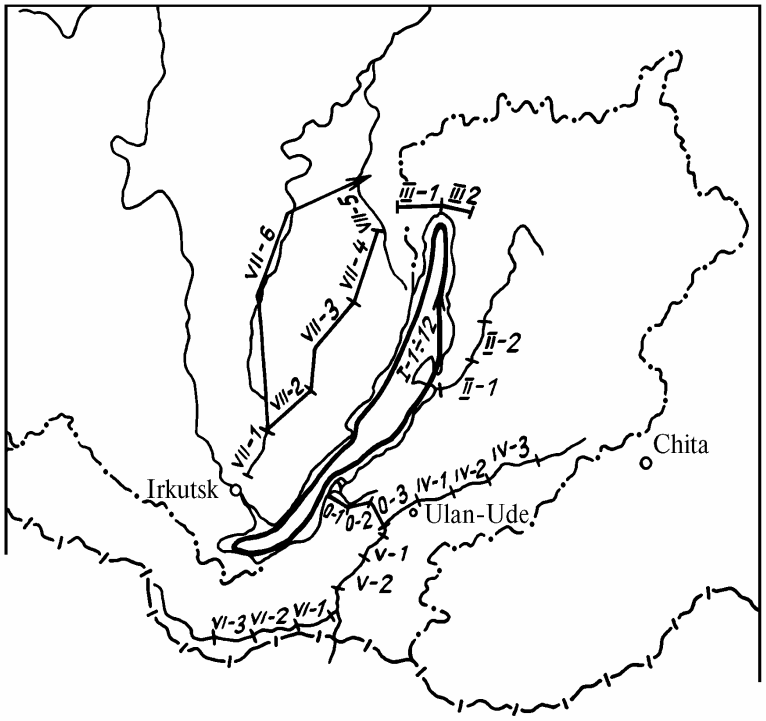

FIG. 4. Scheme of regional photography of Baikal Lake and Buryat: Roman numerals and numbers indicate the serial numbers of the route and its sections, respectively.

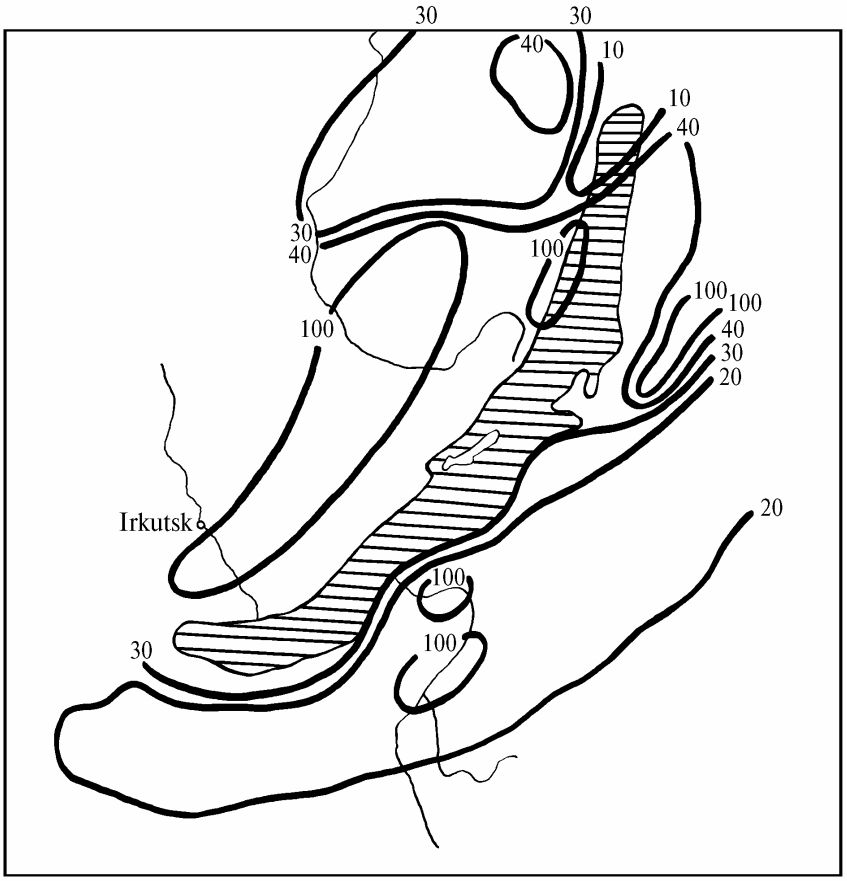

FIG. 5. Aerosol mass concentration (μg/m³) within the 40–600 m altitude range over the Baikal region.

To confirm the importance of the regional approach and to demonstrate the fact that administrative boundaries have no effect on the spread of pollution, we present a map of the distribution of aerosol mass concentration over the Baikal region (Fig. 5).

It can be seen from Fig. 5 that there is a large area of enhanced concentration of suspended substances on the west of Baikal Lake. This area is engendered by the activity of the Irkutsk industrial zone (Fig. 1). The barrier effect of the mountain ridge stretched north–west of the lake promotes the aerosol accumulation. The small–scale areas of high aerosol concentrations on the east shore of Baikal Lake are caused by the hydrodynamic concentration of pollutants in the valleys of the Selenga and Barguzin rivers to which they are transported from the west.

Additional peculiarity was revealed during sounding of pollutants over Baikal Lake. The mountain ridges are situated around the lake so that the flux of pollution from the Irkutsk industrial zone can enter only the southern end of the lake. But the comparison of concentrations in different parts showed their proportionality. The analysis of such a situation made it possible to identify a closed air circulation in the lake hollow along its contour.[14] This circulation promotes the spread of pollutants.

In this experiment we made photographs on a 1:200,000 scale inside of a 1:1 M scale fragments to investigate the pollutants in more detail. We photographed Ulan–Ude along 15 equidistant flight lines (with a step of 7.5 km) 100 km long. Aiming of the aircraft to each course was performed with the help of aerophotographic instrumentation with an error of ± 50 m.

Maps used to estimate the contribution of the emissions of the industrial enterprises of Ulan–Ude against the background of the regional transfer were constructed from the obtained data.

Thus, by comparing the problems solved by the transboundary and regional sounding methods, it should be noted that the regional method is much more informative and can be used to study not only the transfer of pollution, but also its distribution and dynamics.

COMPREHENSIVE ECOLOGICAL OBSERVATION OF CITIES

The aircraft–laboratories were used not only for transboundary and regional sounding and carrying out of individual experiments, but also for monitoring of the urban pollution.[15–17] However, there are no generally accepted schemes and methods of urban monitoring.

Therefore, we had to make up for this deficiency in going to the study of the distribution and the dynamics of the urban pollution. The procedures were laid down for determining the budget of substances that enter the city from outside, are emitted in its territory, and leave the city; for mapping the distribution of pollution over the city and in its territory (the latter was measured by a ground–based mobile complex); and, for measuring the composition and calculating the amount of emission of large sources.

In order to determine the pollution budget in the city, we needed to measure the mean concentration of pollutants and the wind velocity along the perimeter at different altitudes. The budget was estimated by the law of mass conservation in the following form:

$$B = \int_l \int_0^H C_i(l, h)\, U(l, h) \cos(\hat{U, l})\, dl\, dh$$

or

$$B = \oint\oint_S C_i(s)\, V(s) \cos(\hat{U, s})\, ds + \oint\oint_S \int_0^H Q_i\, ds\, dh,$$

where l is the coordinate along the perimeter of the city, h is the current altitude above the ground, s is the surface element, C_i is the concentration of the pollutant under investigation, U is the wind velocity, $\cos(\hat{U, l})$ is the cosine of the angle between the wind direction and the boundary of the section, $\cos(\hat{U, s})$ is the cosine of the angle between the wind direction and the surface element, and Q_i is the rate of generation of the ith pollutant in the territory of the city. The second formula is more preferable since it can be used to estimate not only the horizontal budget, but also the vertical one (sedimentation and generation).

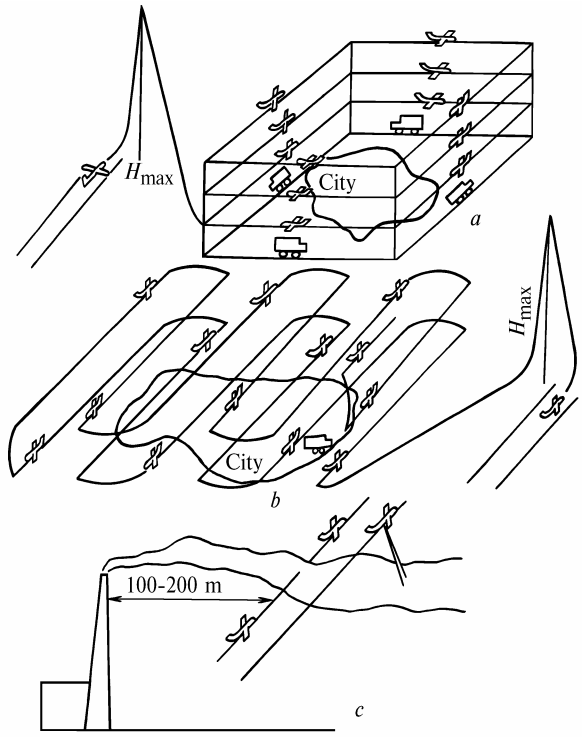

FIG. 6. Scheme of flights for ecological investigation of cities.

This kind of urban ecological observation was implemented according to the following scheme (Fig. 6 *a*). At first, vertical sounding of the atmosphere was carried out up to the maximum altitude, as shown at the left of Fig. 6 *a*. It was aimed at determining the temperature and wind stratifications, the height of the mixing layer, and the peculiarities of the vertical profiles of pollutants. Then the aircraft–laboratory flew horizontally along the square or rectangle tracts enclosing the city. The flights were conducted at different altitudes at 100–m intervals from the minimum altitude available for the given locality to the height of the upper boundary of the mixing layer. One test flight was conducted above the mixing layer. The concentration of pollutants at the ground was determined with the help of a ground–based mobile station.

In addition to the concentration of pollutants, the meteorological and navigation parameters were recorded in flight. Independently of the area of the city, this kind of observation must be accomplished in the course of one day with stable weather and wind direction constant in time and altitude. The budget was calculated by any formula given above. The total error in determining the budget could change from 35 to 60% depending on the selected parameter, weather conditions, and geographical peculiarities of the locality.

The pollution budgets for some cities of the Commonwealth of Independent States (CIS) are given in Table I. They show the increment to the mass of pollutants when air mass passes through the territory of the city. As a rule, it is several hundred thousands of tons per year. The Khabarovsk region, where we obtained relatively small value, is the only exception. This fact is explained below.

TABLE I. Budget of pollutants (tons per year) in cities.

City	Season	Budget
Nizhnevartovsk	winter	266357
	summer	189513
Pavlodar + Ermak	spring	1977140
Khabarovsk	summer	5430
Ust'–Kamenogorsk	spring	780767
Ulan–Ude	fall	79154

Since the information about such observations is lacking, we failed to compare directly the obtained results with independent data. However, some examples of measurements of the fluxes of air pollutants through the vertical surface were reported in the literature.[15,18] Since these fluxes are used to calculate the budget by this method, this comparison is reasonable and correct.

It can be seen from Table II that the fluxes are comparable regardless of the region. On the one hand, this confirms the correctness of flux measurements. On the other hand, the question now arises of the magnitudes of these budgets (Table I) since such values cannot be obtained by simple summing up the emissions.[19] Possibly, this is due to the peculiarities of calculation: in one case they are performed by the procedure for the limited number of components; in another case, a larger number of components after their condensation, transformation, etc. are directly measured in the atmosphere. Evidently, only the special experiments can answer this question.

The following kind of operation in urban ecological observation is mapping of the distribution of air and near–ground pollutants. Air pollutants were mapped with the help of the aircraft–laboratory and near–ground pollutants – with the help of the mobile station. It is schematically shown in Fig. 6 *b*.

TABLE II. Pollution mass fluxes (kg/s·km) transferred through the unit of vertical surface.

Component	Megion	Nizhne–vartovsk	Samotlor	Netherlands Ref. 18	Mariupol' Ref. 15
Nitrogen oxide	42.8	98.1	20	44.7	–
Carbon oxide	100	–	–	60.6	–
Sulphur dioxide	1.7	15.8	9.7	64.9	–
Suspended substances	1.4	2.5	5.1	13.1	16.4–31.1

At first, in analogy with the case of the budget estimation, vertical sounding is carried out in order to determine the thermodynamic stratification and the altitude profiles of pollutants.

The altitudes of horizontal sections (levels) were selected based on the obtained vertical profiles. These criteria are well known,[20] therefore we will not dwell on this question. It should be only noted that the mapping altitudes are not *a priori* known except the minimum altitude, but are determined in flight. In this kind of sounding the flight line and the number of the flight routes of the aircraft–laboratory are preassigned. As a rule, the routes are equally spaced. The number of routes can vary from 6 to 12 depending on the area of the city. After recording of the parameters at one altitude, the aircraft–laboratory flies at the consecutive altitude, and so on for all the preselected altitudes. The number of altitudes can vary from 3 (under conditions of low ground inversion) to 6 (under conditions of intensive mixing in summer).

The sounding data are subsequently used for mapping of the distribution of different components at every altitude of sounding. Intercomparison of these maps is used to pattern the volume distribution of pollutants over the city, while their temporal variations are used to estimate the dynamics of generation and transfer of pollutants.

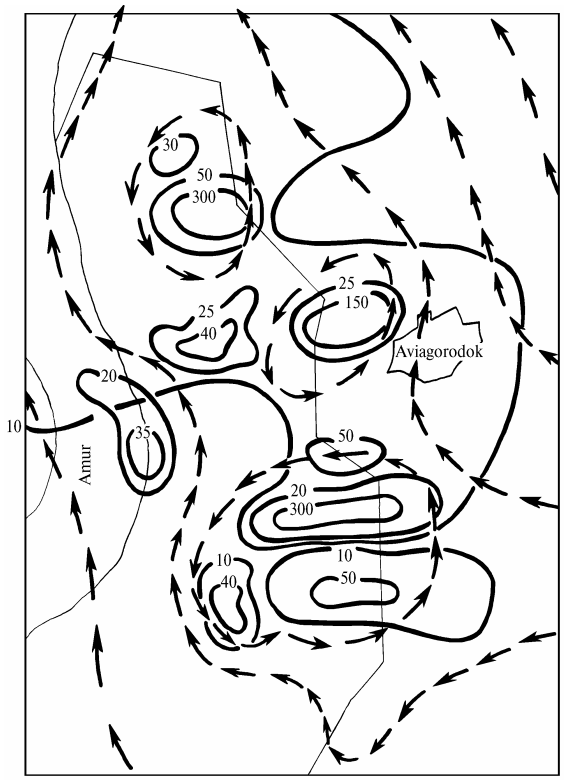

FIG. 7. Number density (–) and flow lines (→) at an altitude of 400 m over Khabarovsk in June, 1990.

In our earlier papers[21,22] we gave some examples of maps that demonstrate the peculiarities of the distribution of pollutants over different cities. In addition to this merit, which is more interesting for the specialists on protection of the environment, these maps have one more merit. They can be used to explain one or the other of peculiarities of the obtained distribution by means of comparing different air characteristics. The above–discussed points are illustrated by Fig. 7 that shows the results of comparison of the aerosol number density distribution over Khabarovsk with the air flow lines at the same altitude. It can be seen from Fig. 7 that circulations occur in the wind field over the city. These circulations result in concentrating aerosol inside them. This effect also explains the small value of the pollution budget of this city (see Table I).

The sounding scheme shown in Fig. 6 *b* has one more purpose. It is the determination of the scales of inhomogeneities in the spatial distribution of pollutants over the city. It is necessary for choice of the grid step for placement of sites of ground–based system of air monitoring of the CITY type. The review of the available methods of choosing the efficient step for location of the ground–based station network and the number of stations was given in Ref. 23. This review also discusses their merits and demerits.

One possible way of solving this problem is the calculation by correlation (structure) functions of the pollution distribution.[24,25] Following this approach we note that calculation of the functions from the data obtained with the help of ground–based systems located within the city is fraught with great errors due to the effect of the local factors. In our opinion, calculation of the autocorrelation functions from the data of airborne sounding at altitudes of 100–200 m is the best approach. The validity of generalization of the results obtained at an altitude of 100 m to the ground layer can be substantiated by the fact that according to the earlier data,[26] the scales of pollution inhomogeneities decrease with altitude. Therefore, the network step will not be overestimated with decrease of the altitude.

The experiments carried out over a number of industrial centers (Khabarovsk, Pavlodar, Nizhnii Tagil, Nizhnevartovsk, etc.) showed that the step of the network stations determined by this procedure can vary from 0.8 to 5 km. The important peculiarity of such an approach is the fact that the correlation length depends on the degree of concentration of the arranged sources. It decreases for many sources and increases without them. That makes it possible to decrease the number of surplus ground–based stations determined theoretically.[25]

The third kind of sounding for urban ecological observation is the determination of the parameters of emission from large sources and their composition and amount. Usually, composition and amount of emission are calculated on the basis of the technology or are determined by collecting samples from the smoke stacks. In this case the physical–chemical changes which may occur in the composition of gas–aerosol mixture spreading through the stack and entering the atmosphere are not taken into account.

It should be noted that a lot of measurements were performed with the aircraft–laboratories flying in the emission plumes. But as a rule, they were of a particular character and reduced either to the detection of one or more of emission components or to the investigation of their dynamics in a plume.[15,17,27,28] Such measurements gave no way of deducing a general concept of a large number of substances and amount of their emission. The equipment of the OPTIK–E AN–30 aircraft–laboratory[1] is capable of obtaining the large amount of information about the emission characteristics.

Sounding of emissions of large industrial enterprises was carried out by the scheme shown in Fig. 6 *c*, or by the direct collection of air samples when flying through the plume, or by means of a lidar when flying over the plume.[29] The samples were collected near the stacks, at distances of 100–200 m from their edges. The altitude and direction of the flight were hold in such a manner that the aircraft–laboratory flew through the plume center perpendiculary to it. Filters and containers were exposed only within the plume, other characteristics were recorded continuously.

Aerosol and gas composition of the emissions of some objects is given in Tables III and IV. The comprehensive analysis of Tables III and IV is beyond the scope of this paper since it is mostly related to the environmental protection problems. Let us pay our attention only to a great variety of substances emitted by different objects into the ambient air.

The meteorological and navigation parameters that were simultaneously recorded from onboard the OPTIK–E AN–30 aircraft–laboratory[1] made it possible not only to determine the emission composition, but also to calculate its amount for each object.

Knowing the plume parameters, the wind velocity at the flight altitude, and the mean concentration of pollutants in the plume cross section, we can determine the amount of substance emitted in a unit time

$$Q = \int_s \int C_i(s)\, U(s)\, \mathrm{d}s\ .$$

The estimated total error in determining the amount of emission by this method does not exceed 35%.

Without presenting the data on the amount of emission of different objects, we note that the results obtained by the given procedure may vary from 0.95 of the results of calculations by the technology to 10 times larger. It may happen due to three reasons.

First, the incorrectness of calculation by the technology and impossibility of direct testing of the calculated data.

Second, the nonstationarity of the technological processes and hence the fluctuations of the emission strength. This fact was repeatedly observed in laser sounding of plumes.[29,30] Therefore, the measurements may be performed during a period of maximum or minimum emission and naturally, underestimate or overestimate the amount of emission.

Third, the gas condensation upon exiting the stack and the gas transformation to aerosol as well as moistening of particles should result in the increment to the mass. This is illustrated by Fig. 8 by the example of the transformation of the aerosol particle size distribution at different distances from the edge of the stack. The particle size distribution in the initial part of the plume at a distance of 2 km has a shape shown by curve *1*. After passage of 20 km and taking part in the above–enumerated processes, aerosol distribution transforms into that shown by curve *2*. Curve *3* recorded at a distance of 22 km indicates that the processes of the particle growth continue.

In conclusion it should be noted that after urban ecological sounding not only the comprehensive description of the distribution of pollutants of the air basin can be obtained but also the general pattern of their dynamics, as was done for Khabarovsk and Komsomolsk–na–Amure.[22] It provides a basis for guiding the development of the systems of routine monitoring of the air basin of the given city and for evaluating potential ways of salvaging our environment which can be implemented just after the experiment.

TABLE III. Chemical composition (μg/m^3) of aerosol emissions.

Component	Region						
	Samotlor		Ermak	Khabarovsk		Kamchatka	Baikal Lake
	Object						
	Oil plume	Gas plume	State regional power station	Heat–and–power station 1	Heat–and–power station 3	Volcano	Irkutsk plume
pH	6.37	6.35	–	–	–	–	5.63
Na^+	18.30	5.17	50.00	675.00	153.30	5.10	0.91
K^+	<	<	11.70	820.00	316.70	0.83	0.03
Cl^-	112.10	<	69.50	665.00	443.00	0.76	34.41
NH_4^+	<	<	225.00	<	346.60	15.20	1.20
SO_4^{2-}	<	<	201.57	<	<	18.00	<
Hg^{2+}	<	0.19	45.00	1.90	<	<	<
Zn^{2+}	<	<	4.52	33.50	22.40	<	<
Cd^{2+}	<	<	0.20	<	16.70	<	<
Br^-	<	<	80.00	–	–	<	<
NO_3^-	<	<	30.00	40.00	6.90	<	<
As^{5+}	<	<	53.30	46.80	51.30	<	<
Fe	4.38	6.12	520.00	580.00	200.00	19.50	12.23
Mn	0.04	0.003	10.00	3.20	2.50	0.46	0.12
Mg	4.25	<	23.30	110.00	51.70	2.60	0.14
Pb	0.14	0.07	0.27	<	<	<	<
Cr	0.10	<	50.20	8.25	2.70	0.16	20.34
Ni	0.41	0.08	9.00	2.82	16.00	0.50	1.11
Al	242.50	3.22	1100.00	460.00	620.00	9.05	1.10
Ti	12.00	5.32	80.00	8.50	<	3.50	0.09
Cu	0.28	2.13	8.10	14.00	4.50	0.08	0.32
V	0.03	<	1.00	6.00	1.00	0.10	0.01
Mo	<	<	<	1.00	5.80	<	0.52
Ca	13.75	3.54	255.00	1700.00	1016.70	38.90	0.83
Si	0.63	0.03	943.30	7100.00	1266.70	13.40	<
Ba	1.56	<	<	<	<	0.78	0.51
B	0.06	<	0.19	<	0.30	0.04	<
Co	<	<	0.06	<	<	0.20	0.02
Cd	<	<	170.00	78.00	16.70	<	<

Note: < denotes the amount less than a threshold of detection and – refers to the substance that was not detected.

TABLE IV. Gas composition of emissions (mg/m^3).

Component	Region				
	Samotlor		Megion	Khabarovsk	
	Object				
	Oil plume	Gas plume	Boiler–room	Heat–and–power station 1	Heat–and–power station 3
Ammonium	1.90	0.20	<	0.2	0.2
Acetylene	<	<	<	3.0	3.2
Benzine	31.00	2.22	12.40	–	–
Benzene	1.80	1.20	0.50	–	–
Xylene	9.60	10.80	5.20	–	–
NO	1.20	1.30	0.10	6.0	7.2
NO_2	0.08	0.20	0.08	0.3	0.1
CO	3.20	3.90	5.60	2.0	15.0
SO_2	1.80	1.60	0.80	0.8	0.6
H_2S	<	<	<	0.8	0.2
Cl_2	<	<	<	0.1	0.5

Note: < denotes the amount less than a threshold of detection and – refers to the gas that was not detected.

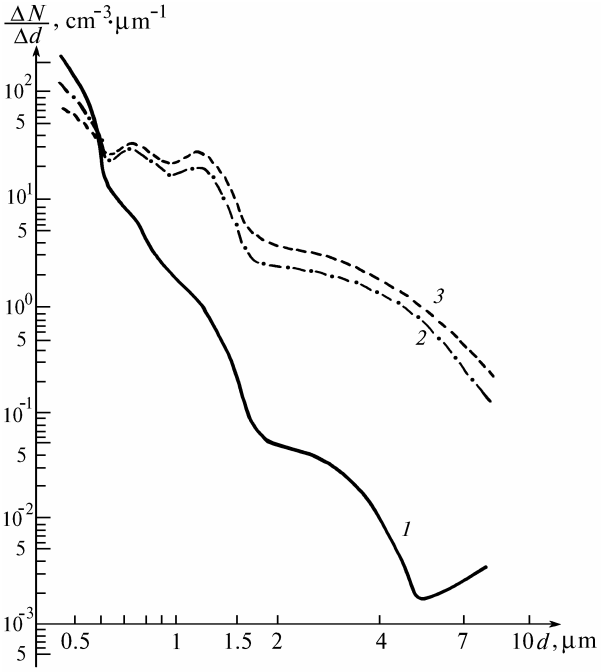

FIG. 8. Aerosol particle size distribution in the Amursk plume at a distance of 1) 2 km, *2)* 20 km, *and 3)* 22 km *from the edges of stacks.*

CONCLUSION

The aforementioned methods of application of the aircraft–laboratories to monitoring of the air state encompass practically the entire range of variation scales of the pollution field from global to local. The results of validation of these methods show the effectiveness of the aircraft–laboratories for any scale. However, the earlier experience and the described merits and demerits of the airborne method of ecological monitoring convince us that regional monitoring including transboundary and local monitoring is its most optimum application. This paper gave no consideration to the possible application of the aircraft–laboratory in emergencies where its usage is no less effective.

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