

UDC 551.511.61+551.578.46

Investigation of Aerosol Precipitation of Polyaromatic Hydrocarbons in the Sphere of Influence of Barnaul

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(Received August 12, 2010; revised February 18, 2011)

Abstract

Results of the field studies, chemical analytical and numerical investigation of the pollution of the snow cover in the zone affected by the sources in Barnaul emitting polycyclic aromatic hydrocarbons (PAHs) are reported. By means of gas chromatography/ mass spectrometry, 19 individual PAH were determined in the collected snow samples. Numerical analysis of the experimental data was performed, and the quantitative regularities of the regional emission of PAHs from the territory of Barnaul were found. By means of the correlation analysis, a linear dependence was established between average logarithms of PAHs concentrations measured in the vicinity of stationary meteorological posts at the territory of the city and beyond its bounds at the direction of prevailing drift. The possibility to construct an economic system of monitoring for estimation of the urban atmospheric pollution for a long-term period was demonstrated.

Key words: atmosphere, pollution, aerosol, polyaromatic hydrocarbons, snow cover, observation data, numerical analysis

INTRODUCTION

Arrangement of instrumental observations of aerosol pollution over a large area and for a long time represents substantial difficulties. Because of this, environmental monitoring often involves natural pads accumulating aerosol matter. For instance, snow cover serves as one of the most reliable indicators of atmospheric pollution of urban territory and suburbs [1-3]. Such highly toxic substances as polycyclic aromatic hydrocarbons (PAHs) are detected in precipitated matter [4]. These compounds are formed as the products of incomplete combustion of organic fuel. Especially large amount of

PAHs emission is observed during winter as a result of coal combustion at heat and power stations and in the houses of private sector. The contribution of motor transport into the pollution of urban atmosphere is also substantial.

As a consequence of the complicated structure of the spatial-temporal distribution of emission sources, the field of PAHs concentrations in the urban atmosphere is rather heterogeneous. In order to evaluate it, the system of stationary meteorological stations is commonly used [5]. However, the efficiency of the system of stationary sites is very limited, especially if we take into account the fact that new pollution sources arise at the city territory, and

the motor transport stock is increasing rapidly. In this connection, the necessity to substantially broaden the system of observation sites and to evaluate its information content arises.

On the other hand, the city territory can be considered as an area source of pollution, the impact of which is substantial over several tens kilometres [1, 2]. On the basis of external action, it is possible to evaluate its total emissions, multicomponent composition of precipitating admixtures. The direct numerical modelling of the propagation of admixtures from the city territory requires complicated mathematical models involving a substantial number of parameters that need further determination and refinement [6]. However, such a work is hindered by the existing technical and economical possibilities. Such a situation requires more weighed joint use of the data of experimental observations and theoretical considerations within the framework of corresponding formulations of inverse problems of impurity propagation in the ground and boundary atmospheric layers.

The goal of the present work was to establish the regularities of the distribution of PAHs component composition in snow over the territory of Barnaul and outside the city. In this connection, we carried out field observations with snow sampling at the territories under examination, chemical analysis of samples over the major PAHs compounds, numerical analy-

sis of the data of observations related to the transport of impurities from an area source.

FIELD INVESTIGATION

According to the schedule of experimental work, to determine major PAHs compounds, snow sampling was performed in early March 2009 both at the territory of Barnaul and outside it. It should be noted that the Altay Centre for Hydrometeorology and Environmental Monitoring (CHEM) performs control of air pollution in Barnaul only with benzo(a)pyrene and only at two stationary observation sites, which is surely insufficient to provide an objective evaluation of the state of urban atmosphere [7].

Inside the city, snow samples were collected near the stationary meteorological stations. The number of these permanently operating stations is equal to five at present. Their arrangement and winter mean climatic characteristics of wind direction recurrence are shown in Fig. 1 [7, 8].

Outside the city, snow sampling was carried out along the routes confined to the north-eastern direction of admixture transport. According to the winter wind rose, the maximal amount of urban emissions enters this sector [9]. Taking into account the existing road system and the positions of the major suburban

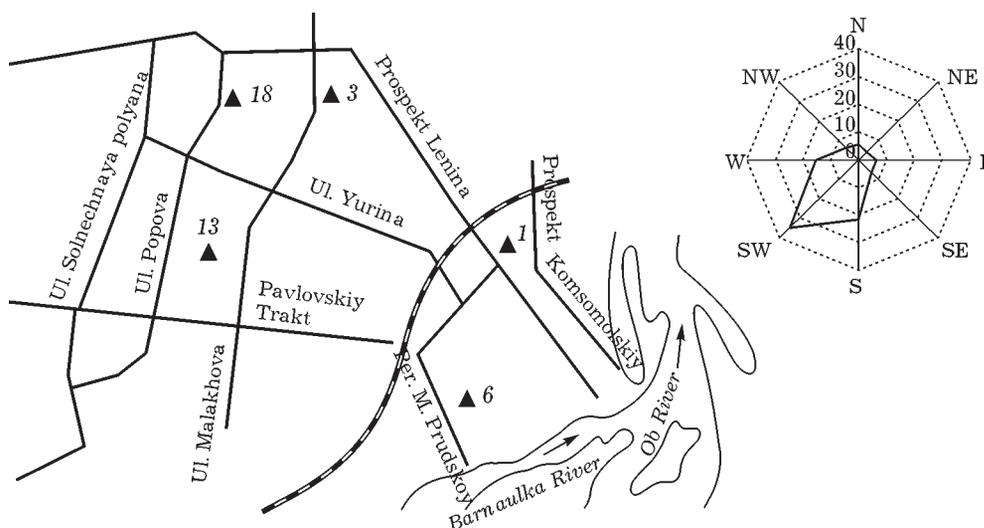


Fig. 1. Arrangement of stationary meteorological stations Nos. 1, 3, 6, 13, 18 of the Altay Centre for Hydrometeorology and Environmental Monitoring (Barnaul).



Fig. 2. Scheme of snow sampling sites in the vicinity of Barnaul. Figures indicate the numbers of observation points; A, B are sampling routes.

local sources (the towns of Beloyarsk and Novoaltaysk), two routes of snow sampling were chosen. The distribution of points along the routes was made according to the assumed dynamics of concentration decrease with an increase in the distance from the city territory [10]. The scheme of sampling routes is presented in Fig. 2.

Snow was sampled with the help of a plastic tube 45 mm in diameter. Sampling procedure included cutting a core over the whole depth of snow cover to the basis of its bedding. The core was purified from the residues of soil and/or plants in the bottom part and placed into a polyethylene pack. The number of cores in one pack for each sampling site was such that the total sample mass was 1.0–1.5 kg.

CHEMICAL ANALYSIS

A standard procedure described in [11] was used to determine PAHs. The procedure included the following stages: sample melting at room temperature; addition of witness compounds that allow us to follow the completeness of PAH extraction; triple extractive concentrating of PAHs into preliminarily distilled ethyl-

ene chloride from the whole volume of non-filtered melted snow sample. United extracts were dried with anhydrous sodium sulphate; the solvent was evaporated using a rotary evaporator at a temperature of 35 °C till dry residue was obtained. The residue was dissolved in 1 mL of acetone. The resulting solution was analyzed for PAHs content by means of gas chromatography/mass spectrometry using an Agilent Technologies (AT) 6890N gas chromatograph and AT 5975N quadrupole mass spectrometric detector in the mode of detection relying on the individual characteristic ions of compounds under determination. The components for analysis were separated at a HP-5MS capillary quartz column 30 m long, 0.25 mm in diameter and coating thickness 0.25 µm. The conditions of gas chromatographic determination were: detector temperature 280 °C, temperature of ion source 230 °C, quadrupole temperature 150 °C, carrier gas – helium. The temperature of thermostat holding the column was increased from 50 (exposure: 2 min) to 280 °C (exposure: 20 min) at a rate of 10 °C/min. A standard PAHs mixture (Hewlett Packard No. 8500-6035) was used to calculate the concentrations. The error of determination of indi-

vidual PAHs was $\pm 20\%$. Correctness of results was verified by adding standard samples of brominated and deuterated derivatives of PAHs into the initial sample before extraction.

The following 19 PAHs compounds were determined in all the samples of snow cover: phenanthrene, fluoranthrene, pyrene, naphthalene, fluorene, acenaphthylene, chrysene, anthracene, benzo(e)pyrene, benzo(b)fluoranthrene, benzo(k)fluoranthrene, benzo(g,h,i)perylene, indeno(1,2,3-cd)pyrene, benzo(a)pyrene, benzo(a)anthracene, acenaphthene, benzo(j)fluoranthrene, perylene and dibenzo(a,h)anthracene. The results are shown in Table 1.

MODELS TO EVALUATE REGIONAL POLLUTION AND NUMERICAL ANALYSIS OF OBSERVATION DATA

The data of field observations and numerical modelling provide evidence that under normal conditions the concentration of an impurity in

the boundary atmospheric layer at a distance of 7–10 km from pollution source is determined by relatively small number of factors. These factors first of all include the source power, average velocity of wind and the thickness of mixing layer. In this case, the field of pollutant concentration from a point source, averaged for a long time interval, is described by equation [10]

$$Q(x,y) = \lambda M g(\varphi(x,y,\xi,\eta)) / [2\pi u h d(x,y,\xi,\eta)] \quad (1)$$

where (x,y) are Cartesian coordinates of the calculated point; (ξ,η) are the coordinates of

the point source; $\varphi(x,y,\xi,\eta) = \arctg \left(\frac{y-\eta}{x-\xi} \right)$,

$d = \sqrt{(x-\xi)^2 + (y-\eta)^2}$; $g(\varphi)$ is the probability of wind direction opposite to φ at a height of the boundary atmospheric layer; λ is the coefficient of impurity interaction with the underlying surface; M is source power; u , h are average wind velocity and the thickness of mixed layer, respectively.

Passing to the areal sources, evaluation problem becomes much more complicated because

TABLE 1

PAHs concentrations in snow samples at stationary meteorostations and in the suburbs of Barnaul

Components	Station No.					Numbers of sampling sites at suburban routes											
	1	3	6	13	18	1	2	3	4	5	6	7	8	9	10	11	12
Acenaphthylene	69	31	200	190	210	44	37	18	25	21	13	16	12	22	13	22	10
Acenaphthene	21	14	33	37	45	31	22	12	24	12	9.0	10	7.2	7.8	5.8	6.4	6.3
Naphthalene	130	52	330	88	470	170	60	28	51	41	15	25	12	67	45	15	20
Fluorene	92	73	230	230	240	54	45	23	44	29	25	22	19	18	12	12	16
Phenanthrene	290	160	1100	990	680	95	180	67	100	230	63	61	68	48	42	37	50
Anthracene	57	73	100	120	67	14	56	12	17	25	8.3	7.7	14	6.7	6.8	5.8	10
Fluoranthrene	200	85	700	820	370	71	260	56	71	270	43	46	71	36	33	25	56
Pyrene	130	58	530	560	270	54	170	37	50	160	29	29	44	24	22	15	33
Benzo(a)anthracene	20	10	110	100	55	15	40	8.3	6.9	5.9	3.2	2.5	4.3	2.8	3.9	1.9	3.2
Chrysene	54	27	230	240	130	48	160	25	22	51	15	15	37	13	22	10	29
Benzo(b)fluoranthrene	35	13	200	170	110	28	62	16	17	26	11	8.3	14	8.9	9.5	5.1	10
Benzo(k)fluoranthrene	32	16	160	160	87	24	48	18	17	27	12	9.8	19	9.2	10	5.6	11
Benzo(j)fluoranthrene	4.9	2.5	25	28	17	4.0	7.5	2.1	2.7	2.9	1.7	1.1	1.8	0.8	1.4	0.8	1.2
Benzo(e)pyrene	34	18	180	160	120	24	46	13	18	25	12	8.6	13	7.8	9.6	5.3	8.8
Benzo(a)pyrene	20	7.3	120	100	67	16	31	7.7	7.2	11	4.9	3.9	6.6	2.9	5.1	3.4	4.6
Perylene	3.3	1.7	18	22	16	3.4	5.3	1.4	3.0	1.9	1.0	0.5	1.0	0.8	1.0	0.4	0.7
Dibenzo(a,h)anthracene	2.5	1.0	19	14	15	1.3	2.9	1.0	1.4	0.8	1.1	0.6	1.0	0.5	0.7	0.5	0.6
Indeno(1,2,3-cd)pyrene	25	11	140	150	97	22	32	12	11	17	9.8	5.9	15	5.8	7.5	4.7	5.0
Benzo(g,h,i)perylene	28	11	150	130	120	21	24	11	16	18	12	7.6	1.0	6.9	7.7	2.8	6.1
ΣPAHs	1248	665	4575	4309	3187	739	1289	368	503	976	289	280	362	288	258	179	283

the amount of admixture emitted is unknown and it is distributed non-uniformly over the city territory. Taking into account eq. (1), the density of precipitated aerosol admixture in the case of the areal source S will be

$$Q(x, y) = \frac{\lambda}{2\pi u h} \iint_S \frac{m(\xi', \eta') g(\varphi)}{d} d\xi' d\eta' \quad (2)$$

where $(\xi', \eta') \in S$, (ξ', η') are the current coordinates of the source; $m(\xi', \eta')$ is emission of the impurity from this point. It is also assumed that point (x, y) is located at a sufficiently large distance from variety S .

In practice, emission capacity $m(\xi', \eta')$ from the city territory is unknown or can be set only very roughly. Under these conditions, it is difficult to interpret observation data with the help of eq. (2). In this case, in order to provide approximate description of concentration field in the vicinity of an area source, it is necessary to use the methods of asymptotic expansion of the potential theory [12]. Outside the city territory, for a fixed direction φ , rather good approximation to eq. (2) can be used [10]:

$$Q(x, y) = \frac{\lambda M g(\varphi(x, y, x_0, y_0))}{2\pi d(x, y, x_0, y_0)} \iint_{\Omega} \frac{B(u', h')}{u' h'} d\Omega = \frac{\theta g(\varphi)}{d} \quad (3)$$

Here (x_0, y_0) are the coordinates of effective emission centre at the territory of the areal

$$\text{source } S; \quad \theta = \frac{\lambda M}{2\pi} \iint_{\Omega} \frac{B(u', h')}{u' h'} d\Omega,$$

$M = \iint_S m(\xi', \eta') d\xi' d\eta'$, $B(u, h)$ is the probability density for the distribution of u, h values within the time interval under consideration.

Using eq. (3), one may obtain an estimation of unknown parameter θ on the basis of measurement data in the definite points of the density of aerosol precipitation of admixture outside the city borders.

Preliminary examination of measurement data (see Table 1) showed generally monotonous decrease in PAHs component precipitation along routes A and B, which allows us to perform their quantitative analysis on the basis of regression relationship (3). The results of numerical interpretation for some measurement data (for benzo(a)pyrene, phenanthrene, total amount of PAHs) along route A are presented in Fig. 3. One can see that calculated data exhibit quite satisfactory coincidence with ob-

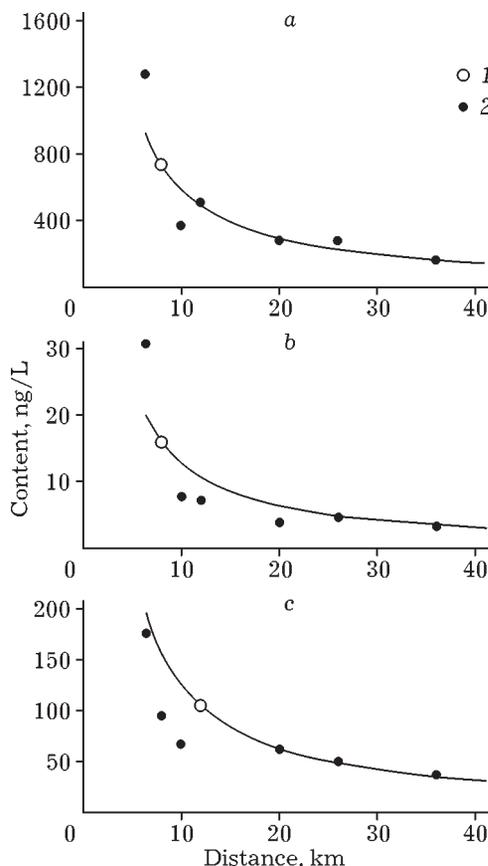


Fig. 3. Measured and numerically reconstructed concentrations of total PAHs (a), benzo(a)pyrene (b) and phenanthrene (c) in snow samples along route A. Observation points: 1 - reference, 2 - control.

servation results for the majority of control points, and this fact serves as an additional confirmation of the dominating effect of emissions from Barnaul on the formation of PAHs concentration levels in the chosen observation points. In particular, we succeeded in avoiding substantial contribution of PAHs emission from the territory of Novoaltaysk because sampling scheme does not include the area in which this effect can be pronounced.

It should be stressed that the background PAHs concentration could be estimated formally having included into regression eq. (1) an additional unknown parameter that takes account of the contribution from the background. However, within the framework of regression (1), the results of numerical modelling are in good agreement with the data of PAHs measurements in the zone of regional emissions from Barnaul, which points to relatively low back-

ground level. So, the estimation procedure proposed above loses its significance.

CORRELATION ANALYSIS OF THE DATA OF PAHs CONCENTRATION MEASUREMENTS

Investigation of the problem of snow cover pollution with anthropogenic emissions over large areas and subsequent construction of a mesoscale model of pollutant transport appear to be undoubtedly interesting. A city should be considered as an area source of pollutants.

Though the extent and composition of aerosol pollution in the region under investigation are extremely variable, there are reasons to suppose that stable interrelations can exist between the average weighted concentrations of components, and the corresponding relations will be approximately the same for the territories with joint emission sources [13, 14]. The procedure used in subsequent studies involved determination of average weighted concentrations of PAHs over the territory of Barnaul

(stations) and subsequent comparison of these data with the values calculated similarly for the adjacent territory (plume).

It was accepted that the empirical functions of density C_i distribution over the number of samples for PAHs, similarly to chemical elements in the snow cover [14], have normal logarithmic character. In this connection, the geometric mean values $C_{g/m}$ were calculated as the average weighted PAHs concentrations. Table 2 shows the data for $C_{g/m}$, average values of logarithms $\overline{\log C}$ and standard deviations $\sigma_{\log C}$ that may be considered as the model data for evaluating the integral pollution of the territories under investigation, with the total area of about $10 \times 20 \text{ km}^2$.

The comparative analysis of the composition of precipitation was made for all the 19 components at once. Regression lines were drawn through the points with abscissas and ordinates corresponding to the values of component concentrations in two sets under comparison: $y = kx + b$

TABLE 2

Geometric average PAH concentrations at stationary posts and at suburban routes ($C_{g/m}$), their logarithms ($\overline{\log C}$) and standard deviations ($\sigma_{\log C}$)

PAHs	Stationary posts			Suburban routes		
	$C_{g/m}$	$\overline{\log C}$	$\sigma_{\log C}$	$C_{g/m}$	$\overline{\log C}$	$\sigma_{\log C}$
Phenanthrene	500	2.70	0.37	74	1.87	0.24
Fluoranthrene	320	2.51	0.41	64	1.81	0.32
Pyrene	230	2.36	0.42	42	1.62	0.32
Naphthalene	150	2.19	0.40	34	1.53	0.33
Fluorene	150	2.18	0.25	24	1.37	0.21
Acenaphthylene	110	2.04	0.37	19	1.28	0.19
Chrysene	100	2.00	0.41	27	1.43	0.33
Anthracene	81	1.91	0.14	12	1.08	0.28
Benzo(e)pyrene	73	1.86	0.45	13	1.12	0.26
Benzo(b)fluoranthrene	71	1.85	0.50	14	1.15	0.29
Benzo(k)fluoranthrene	65	1.81	0.45	15	1.18	0.25
Benzo(g,h,i)perylene	58	1.76	0.51	8.4	0.93	0.39
Indeno(1,2,3-cd)pyrene	56	1.75	0.50	10	1.01	0.27
Benzo(a)pyrene	42	1.62	0.52	6.7	0.83	0.30
Benzo(a)anthracene	42	1.62	0.45	5.3	0.72	0.37
Acenaphthene	28	1.44	0.20	11	1.04	0.25
Benzo(j)fluoranthrene	11	1.04	0.47	1.9	0.27	0.29
Perylene	8.2	0.91	0.50	1.3	0.10	0.34
Dibenzo(a,h)anthracene	6.3	0.80	0.57	0.90	-0.04	0.22

Parameters k and b were determined by means of the least squares. The Pearson's coefficient of linear correlation (r), calculated using a known procedure, served as a measure of the closeness of component composition. The use of the logarithmic scale is explained by the notion of the lognormal character of concentration distribution law, as well as by the necessity for equivalent account of the contribution from components with high concentrations (for example, fluoranthrene or pyrene) or low ones (perylene) into the coefficient of linear correlation (r).

The total concentration of 19 PAHs compounds in the samples from the Station group vary from 0.7 to 4.6 $\mu\text{g/L}$, and the concentrations of some compounds only slightly vary from one sample to another. For example, the concentrations of anthracene, acenaphthene and fluorine change only by a factor of 2–3. For other compounds, variations may reach 10–20 times. For comparison of PAHs compounds in samples in pairs, the values of the coefficient of linear correlation vary within the range 0.85 to 0.97.

The total content of all the 19 PAHs compounds in the samples from the Plume group varies from 0.2 to 1.3 $\mu\text{g/L}$. The ratios of the maximal and minimal concentrations for different compounds are within the range from 4 to 24. For the comparison of sample composition in pairs, the values of the correlation coefficient vary from 0.77 to 0.97.

The average values of the logarithms of PAHs concentrations measured at meteorological stations ($\overline{\log C_s}$) and under the plume ($\overline{\log C_p}$), with the corresponding standard deviations of logarithms $\sigma_{\log C}$, are presented in Fig. 4. The distributions of PAHs over the logarithms of geometrical mean concentrations in two different sampling zones are very similar to each other: $r = 0.76$.

The coefficients of the equation of linear regression are equal to: $k = 1.00 \pm 0.05$, $b = -0.74 \pm 0.10$. The slope ratio k to the abscissas axis, coinciding with unity within the limits of the confidence interval, provides evidence that not only the logarithms but the geometric mean concentrations themselves C_p and C_s are linearly related to each other. The value of parameter $b = -0.74$ points to the fact that the snow cov-

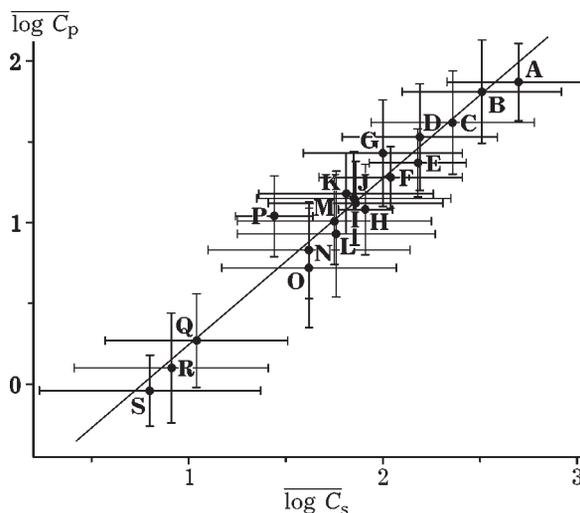


Fig. 4. Comparison of the average logarithms of PAH concentrations for meteorological posts $\overline{\log C_s}$ and plume $\overline{\log C_p}$: **A** - phenanthrene, **B** - fluoranthrene, **C** - pyrene, **D** - naphthalene, **E** - fluorine, **F** - acenaphthylene, **G** - chrysene, **H** - anthracene, **I** - benzo(e)-pyrene, **J** - benzo(b)fluoranthrene, **K** - benzo(k)fluoranthrene, **L** - benzo(g,h,i)perylene, **M** - indeno(1,2,3-cd)pyrene, **N** - benzo(a)pyrene, **O** - benzo(a)anthracene, **P** - acenaphthene, **Q** - benzo(j)fluoranthrene, **R** - perylene, and **S** - dibenzo(a,h)anthracene.

er at the city stations is polluted with PAHs 5.5 times heavier than under the plume.

CONCLUSION

Field, chemical analytical and numerical studies of the pollution of snow cover at the territory affected by the sources of PAHs emissions in Barnaul allow us to make the following conclusions.

Determination of 19 individual PAHs compounds in snow samples collected in the end of winter season of 2008–2009 near five hydrometeorological stations in Barnaul and in its suburbs along the routes confined to the north-eastern sector of pollutants carry-over from the city territory was performed by means of gas chromatography/mass spectrometry.

Numerical analysis of the data allowed us to establish the quantitative regularities of the regional transport of PAHs compounds from the territory of Barnaul. The recovered fields of the density of pollutant precipitation onto

snow cover in the vicinity of the city serve as an integral characteristic of long-term regional influence of the areal source on the environment.

A linear dependence between average logarithms of PAHs concentrations measured at the stationary meteorological stations and in the zone of the maximal regional carry-over of the pollutants from the entire city in general over the range of measured PAHs components was established by means of correlation analysis. It should be stressed that the obtained linear correlation, on the one hand, provides evidence of the identical total emission from the areal source, and on the other hand, confirms the representativeness of the arrangement of meteorological stations in the city with respect to the measured range of PAHs components. Further data analysis revealed the linear dependencies between the concentrations of PAH components at the territories under comparison.

The obtained regularities point to the possibility of arranging an economical monitoring system, evaluation of the pollution of urban atmosphere during a long time interval, and determination of the emission of PAHs components from the city territory.

REFERENCES

- 1 Vasilenko V. N., Nazarov I. M., Fridman Sh. D., Monitoring Zagryazneniya Snezhnogo Pokrova, Gidrometeoizdat, Leningrad, 1985.
- 2 Prokacheva V. G., Usachev V. F., Snezhny Pokrov v Sfere Vliyaniya Goroda, Gidrometeoizdat, Leningrad, 1989.
- 3 Boyarkina A. P., Baykovskiy V. V., Vasiliev N. V., Glukhov G. G., Medvedev M. A., Pisareva L. F., Rezhikov V. I., Sheludko S. I., Aerozoli v Prirodnykh Planshetakh Sibiri, Izd-vo Tom. Un-ta, Tomsk, 1993.
- 4 Rovinskiy F. Ya., Teplitskaya T. A., Alekseeva T. A., Fonovy Monitoring Politsiklicheskikh Aromaticheskikh Uglevodorov, Gidrometeoizdat, Leningrad, 1988.
- 5 Bezuglaya E. Yu., Smirnova I. V., Vozdukh Gorodov i Yego Izmeneniya, Asterion, St. Petersburg, 2008.
- 6 Aloyan A. E., Modelirovaniye Dinamiki i Kinetiki Gazovykh Primesey i Aerozoley v Atmosfere, Nauka, Moscow, 2008.
- 7 Ezhegodnik Sostoyaniya Zagryazneniya Atmosfery v Gorodakh na Territorii Rossii za 2008 g., Asterion, St. Petersburg, 2009.
- 8 Selegey T. S., Formirovaniye Urovnya Zagryazneniya Atmosfernogo Vozdukha v Gorodakh Sibiri, Nauka, Novosibirsk, 2005.
- 9 Koshinskiy S. D., Kukharskaya V. L. (Eds.), Klimat Barnaula, Gidrometeoizdat, Leningrad, 1984.
- 10 Raputa V. F., Olkin S. E., Reznikova I. K., *Optika Atm. i Okeana*, 21 (2008) 558.
- 11 Soniyassi R., Sandra P., Shlett K., Analiz Vody: Organicheskiye Mikroprimesi, Teza, St. Petersburg, 1995.
- 12 Tikhonov A. N., Samarskiy A. A., Uravneniya Matematicheskoy Fiziki, Nauka, Moscow, 1972.
- 13 Pavlov V. E., Sutorikhin I. A., Khvostov I. V., *Optika Atm. i Okeana*, 20 (2007) 96.
- 14 Pavlov V. E., Sutorikhin I. A., Khvostov I. V., *Probl. Bezopasn. i Chrezv. Situatsiy*, 3 (2008) 88.