Monitoring of snow cover pollution alongside highways

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Received November 27, 2001

The model for restoring the short-term pollution of the atmospheric boundary layer by the motor transport is proposed. The areas of intense pollution at different wind directions are determined. The numerical model of the long-term aerosol pollution has been tested using the route snow sampling in the vicinity of Barnaul highway and Sovetskoye highways in Novosibirsk. The structural changes of motor transport aerosol emissions during winter seasons from 1998 to 2001 are under analysis.

Introduction

Methods of estimating the amount of contaminants emitted by vehicles are necessary to develop the measures intended for salvaging our environment. Transport emissions depend on a large number of factors: characteristic categories, intensity and velocity of the traffic, wear of engines, fuel, and so on. There is a series of methods of evaluating the annual emissions of the motor transport in cities, as a whole, and in individual highways.[1–5] Much attention has been given to the study of the atmospheric pollution by carbon oxides. The time dynamics of air pollution and the impact of meteorological conditions were studied in detail. Motor transport pollutants enter the atmosphere also in the form of aerosols of various dispersion and chemical composition.

Propagation of aerosol impurities in the vicinity of highways is as yet little understood both experimentally and quantitatively. The investigations in this field are described in Refs. 6–8, where processes of long-term pollution of the snow cover were studied. Analysis of data on chemical composition of snow with the use of theoretical concepts on the propagation of aerosol impurities in the atmospheric ground layer allowed us to reveal spatial regularities of aerosol fallout of dust, different forms of heavy metals, in particular, lead, polycyclic aromatic hydrocarbons (PAH), and macro-components. Based on the obtained dependences, we evaluated the net emissions from the motor transport for a series of winter seasons and obtained estimates of relative variation of their dispersed composition. The use of the snow cover as an indicator of the level of aerosol pollution presents a unique possibility of effective control for the motor transport emissions under conditions of Siberia. A quite simple procedure of snow sampling enables us to perform a scaled survey in the highway vicinity.

1. Model of single pollution

First we consider the linear source of a finite length located along the axis y in the interval (L_1, L_2). Assume that the horizontal wind direction makes an angle β with the axis x (a reading is taken from the axis x counter-clockwise). Then the propagation of weakly settling impurity from the point source located at a point $\eta \in (L_1, L_2)$ can be described by the following relation[9,10]:

$$q = \frac{M}{(1+n)\, k_1\, \varphi_0\, x_P^2 \sqrt{2\pi}} \times \exp\left(-\frac{u_1 H^{1+n}}{k_1 (1+n)^2 x_P} - \frac{y_P^2}{2\varphi_0^2 x_P^2}\right), \qquad (1)$$

where M is the source power; k_1 and u_1 denote the coefficient of vertical turbulent exchange and the wind velocity per 1 m, respectively; φ_0 is the dispersion of deviations of the wind velocity direction; n is the exponent in the approximation of wind velocity by the power profile; H is the effective source height,

$$x_P = a - \eta\sin\beta;\ y_P = b - \eta\cos\beta;$$
$$a = x\cos\beta + y\sin\beta;\ b = -x\sin\beta + y\cos\beta.$$

By virtue of the principle of superposition, the concentration q_π for a linear source is determined by the equality

$$q_\pi(x, y, \beta) = \Theta_0 \int_{L_1}^{\eta_P} e^{-\frac{\alpha}{x_P} - \frac{y_P^2}{2\varphi_0^2 x_P^{-2}}} \frac{d\eta}{x_P^2}, \qquad (2)$$

where

$$\Theta_0 = \frac{M}{(1+n)\, k_1\, \varphi_0\, \sqrt{2\pi}};\quad \alpha = \frac{u_1 H^{1+n}}{(1+n)^2 k_1};$$

$$\eta_P = \begin{cases} L_2 & \text{at} \quad y + x\cot\beta \ge L_2, \\ y + x\cot\beta & \text{in other case.} \end{cases}$$

0235-6880/02/11 938-05 $02.00

As a result of integration of Eq. (2) we have[1]

$$q_\pi = \frac{\Theta}{x}\exp\left(-\frac{\alpha\cos\beta}{x} + \frac{\alpha^2\varphi_0^2\sin^2\beta}{2x^2}\right)(\mathrm{erf}S_2 - \mathrm{erf}S_1), \quad (3)$$

where

$$\Theta = \frac{M}{2k_1(1+n)}; \; S_i = \frac{\varphi_0\alpha\sin\beta}{x\sqrt{2}} - \frac{\cos\beta}{\varphi_0\sqrt{2}\sin\beta} + \frac{x}{\varphi_0\sqrt{2}\sin\beta(\alpha - A_i\sin\beta)}, \; i = 1,2; \quad (4)$$

$$\mathrm{erf}\, S = \frac{2}{\sqrt{\pi}}\int_0^S \exp(-\xi^2)\,d\xi, \quad A_1 = L_1, \quad A_2 = \eta_P.$$

The analytic expression for the concentration field (3) using the aggregation parameters Θ and α instead of the initial u_1, k_1, H, n, M, enables one to simplify the analysis of the observational data on the atmospheric ground layer pollution. The parameters Θ, α, and φ_0 can be found with the use of Eq. (3) and the observational data by the method of least squares. To increase the accuracy of evaluation, it is expedient to use mathematical methods of design of observations.[11,12] At $L_1 \to -\infty$, $L_2 \to \infty$ from Eq. (3) we obtain the formula for the field of concentration created by an infinite linear source

$$q_\infty(x, \beta) = \frac{\Theta}{x}\exp\left(-\frac{\alpha\cos\beta}{x} + \frac{\alpha^2\varphi_0^2\sin^2\beta}{2x^2}\right) \times \left[1 - \frac{2}{\pi}\int_0^{r(x,\beta)} \exp(-\xi^2)\,d\xi\right]. \quad (5)$$

Here

$$r(x,\beta) = \frac{\varphi_0\alpha\sin\beta}{x\sqrt{2}} - \frac{\cos\beta}{\varphi_0\sqrt{2}\sin\beta}.$$

Formula (5) allows us to obtain a series of useful relationships. In particular, from Eq. (5) it follows that

$$q_\infty(x,\beta)\big|_{\beta=0} = \frac{2\Theta}{x}\exp\left(-\frac{\alpha}{x}\right). \quad (6)$$

In this case, the maximum of Eq. (6) is reached at $x_{\max} = \alpha$. Then

$$q_\infty(x_{\max}, 0) = \frac{(1+n)M}{eu_1H^{1+n}}. \quad (7)$$

Now we consider another extreme position $\beta = \pi/2$:

$$q_\infty(x, \frac{\pi}{2}) = \frac{\Theta}{x}\exp\left(\frac{\alpha^2\varphi_0^2}{2x^2}\right)\left[1 - \frac{2}{\sqrt{\pi}}\int_0^{\frac{\alpha\varphi_0}{x\sqrt{2}}}\exp(-\xi^2)\,d\xi\right]. \quad (8)$$

Using the asymptotic representation of the integral at $x \to 0$ we obtain[4]

$$q_\infty(x, \frac{\pi}{2}) = \frac{\Theta}{x}\exp\left(\frac{\alpha^2\varphi_0^2}{2x^2}\right) \times \left\{1 - \left[1 - \exp\left(-\left(\frac{\alpha\varphi_0}{\sqrt{2}x}\right)^2\right) \Big/ \frac{\alpha\varphi_0\sqrt{\pi}}{\sqrt{2}x}\right]\right\} = \frac{\sqrt{2}\Theta}{\sqrt{\pi}\alpha\varphi_0} = \frac{(1+n)M}{\sqrt{2\pi}\varphi_0 u_1 H^{1+n}}. \quad (9)$$

It follows from Eq. (9) that at the wind directed along the highway the concentration increases essentially as compared with Eq. (7) because usually $\varphi_0 < 0.15$ (Ref. 9).

2. Reconstruction of long-term pollution

Taking into account Eq. (1), the expression for calculating the concentration of pollution nearby some highway can be presented in the form[7]

$$S(x, y, \Theta_0, \Theta_1) = \Theta_0 \int_0^{2\pi}\int_{L_1}^{\eta_P} q(x_P, y_P)\lambda(x_P, \Theta_1)R(\varphi + 180^\circ)\,d\eta\,d\varphi, \quad (10)$$

where

$$\lambda(x_P, \Theta_1) = x_P^{\Theta_1}, \quad \Theta_1 = \frac{w}{k_1(n+1)}, \quad (11)$$

w is the mean settling velocity of aerosol particles, $R(\varphi)$ is the winter mean wind rose for the considered locality. Function $R(\varphi)$ is commonly measured for a discrete set of angles

$$\varphi_j = j\Delta\varphi/N, \quad j = \overline{1, N},$$

where $\Delta\varphi = 2\pi/N$, N is the number of compass points. To obtain the continuous dependence of R on φ, it is useful to apply the following linear interpolation:

$$R_j(\varphi) = P_j + \frac{(P_{j+1} - P_j)\varphi}{\Delta\varphi},$$

$j\Delta\varphi \le \varphi \le (j+1)\Delta\varphi$; P_j is the repetition of wind direction for jth compass point.

Accounting for sedimentation effects does not allow us to simplify Eq. (10) by integration, as in the case of weightless impurity, that results in rather cumbersome expressions. Significant parameters in Eq. (10) are Θ_0 and Θ_1. To estimate these parameters based on Eq. (10), it is necessary to make observations no less than at two points of the area. If the linearity of Eq. (10) relative to Θ_0 is considered, the estimation procedure becomes much more simple and makes it possible to determine Θ_0 and Θ_1 separately. To increase the stability of estimation, it is appropriate to use the optimal scheme of sampling at the stage of experimental investigations. Optimal points of observation can be found, using the algorithms of successive analysis and design of experiment.[11,12]

3. Experimental conditions and design of observations

The pollution of snow cover was studied in the vicinity of the Barnaul highway and Sovetskoye highway in Novosibirsk. The samples of snow were taken early in March 2001 on each side of the highways. The areas of snow sampling in both cases were oriented equally relative to the parts of the world, extended from the southeast to the northwest, and spaced 30 km apart. The region of sampling was homogeneous and practically without vegetation. This allowed us to immediately compare the obtained results and considerably simplify the interpretation of the observational data, since in winter season the repetition of winds of the south and southwest directions is about 60%.

At the area of Sovetskoye highway the route observations were made during four winter seasons that made it possible to follow the dynamics of the long-term pollution, the variation of component and dispersed composition, as well as to assess the total motor transport emissions.[6,7] Using the same scheme, in 2001 the snow samples were taken in the vicinity of the Barnaul highway. Taking into account the processes of aerosol pollution of the highway surroundings, the points of measurement were located in the range from 15 to 90 m. They were located nonuniformly, i.e., close to each other at the nearest end of the interval with more and more wider spaces as they moved farther from this end. Pollution at the range 10–15 m adjacent to the highway depends upon different factors and largely the operation of snowploughs. There must be somewhat correction for variation of particle sizes containing pollutants. At this stage of study this interval should be excluded from consideration.

4. Reconstruction of aerosol deposits

To reconstruct single pollution in the highway locality, it is convenient to apply Eq. (3). In this case it is necessary to use 2 or 3 points of observation. The orientation of highway areas in the locality of sampling allows us to use both a full-size model (10) and a rough model[6] to evaluate the long-term aerosol pollution

$$S(x, \Theta_0, \Theta_1) = \frac{\Theta_0}{x^{\Theta_1+1}} \exp\left(-\frac{\alpha}{x}\right). \qquad (12)$$

The model (10) makes it possible to restore concentration fields of pollutants in snow simultaneously on each side of the highway. In this case we need the information about the wind rose for a given winter season. When using Eq. (12), this information is unnecessary.

4.1. Lead (Pb)

The results of estimating the levels of lead content in snow cover for the Sovetskoye highway with the model (10) are given in Fig. 1.

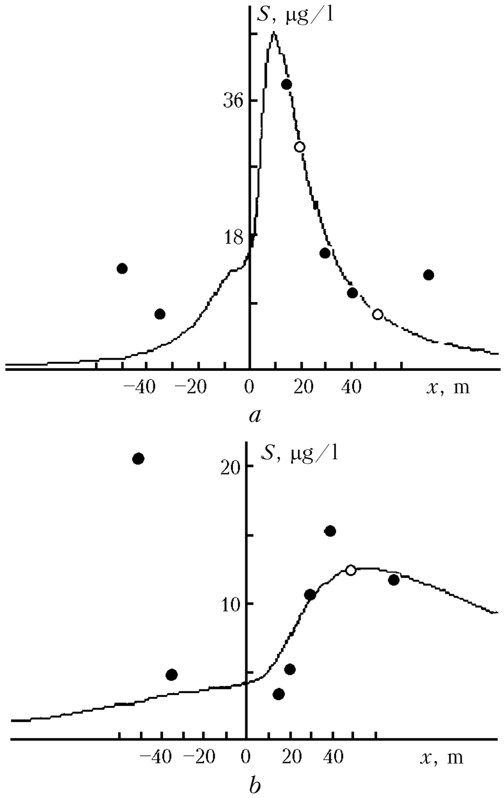

Fig. 1. The distribution of the coarse fraction (*a*) and in aggregate fine and water-soluble (*b*) fractions of lead in snow cover: reference ( ), test points ( ).

The reconstruction of the coarse fraction of lead is given in Fig. 1*a*. Figure 1*b* shows the results of numerical modeling of the total lead content in fine and water-soluble fractions. We used the model (12) corresponding to the weakly settling impurity ($\Theta_1 = 0$). In this case, to reconstruct the regression function, only one observation point removed from the highway at a distance of 50 m was used. Table 1 shows the data on the distribution of water-soluble, fine, and coarse lead fractions at different distances from the highway. The data on the lead distribution during preceding two winter seasons can be found in Ref. 7. Analysis of Table 1 shows that the share of fine and water-soluble fractions of lead increases essentially with distance from the highway. Figure 2 shows the dynamics of lead distribution in fractions during three winter seasons. Figure 2 demonstrates a stronger tendency of contribution of fine and water-soluble fractions, which is connected with the use of lead-free gasoline in motor transport.

Table 1. Share distribution of lead in fractions (%) in winter season 2000/01

Fraction	Distance from the highway, m		
	20	30	50
W	6.3	4.1	27
F	3	23.9	22
C	90.7	72	51

Note. W – water soluble, F – fine, and C – coarse fractions.

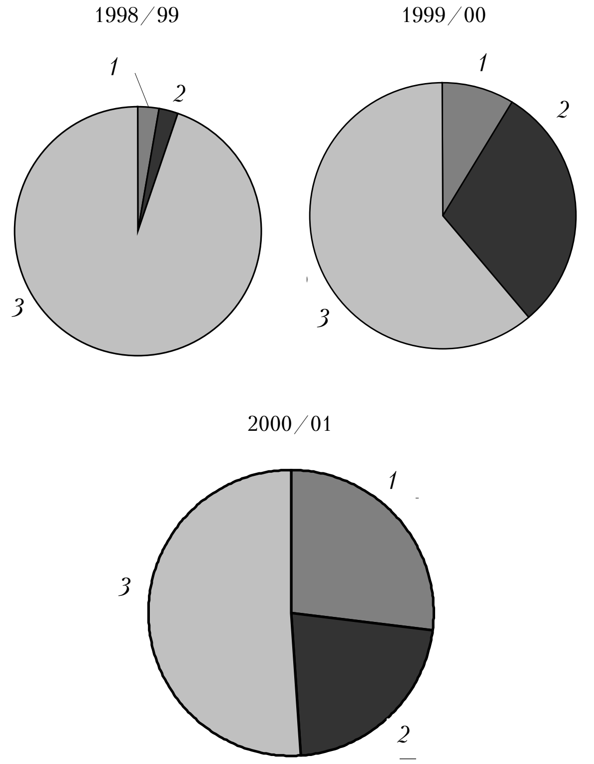

Fig. 2. Lead fraction distribution at a distance of 50 m from the highway during winter seasons of 1998–2001: water-soluble (*1*); fine (*2*); coarse fractions (*3*).

During winter season of 2000–2001 the total content of lead within 10–50 m zone alongside the highway was about 140 g/km. This content is lower than that during 1999–2000 winter season (190 g/km). The total lead content during winter 1998–1999 was 400 g/km (Ref. 7).

4.2. Polycyclic aromatic hydrocarbons

The fields of benz(a)pyrene (BP) concentration in the snow cover were estimated using the observational data for Sovetskoye and Barnaul highways by regression dependences (10) and (12). As reference points of observations, two points were selected on northeast sides of the both highways at distances of 20 m and 50 m. Figure 3 shows the results of reconstruction of pollution fields.

Table 2. Estimates of regression parameters (10) for PAN components

Matter	Barnaul highway		Sovetskoye highway	
	Θ_0	Θ_1	Θ_0	Θ_1
Benz(a)pyrene	510	−2.47	517	−2.38
Perylene	$4.7 \cdot 10^4$	−2.5	$3.2 \cdot 10^4$	−2.53
Pyrene	$3.2 \cdot 10^3$	−2.27	$6.1 \cdot 10^3$	−2.89

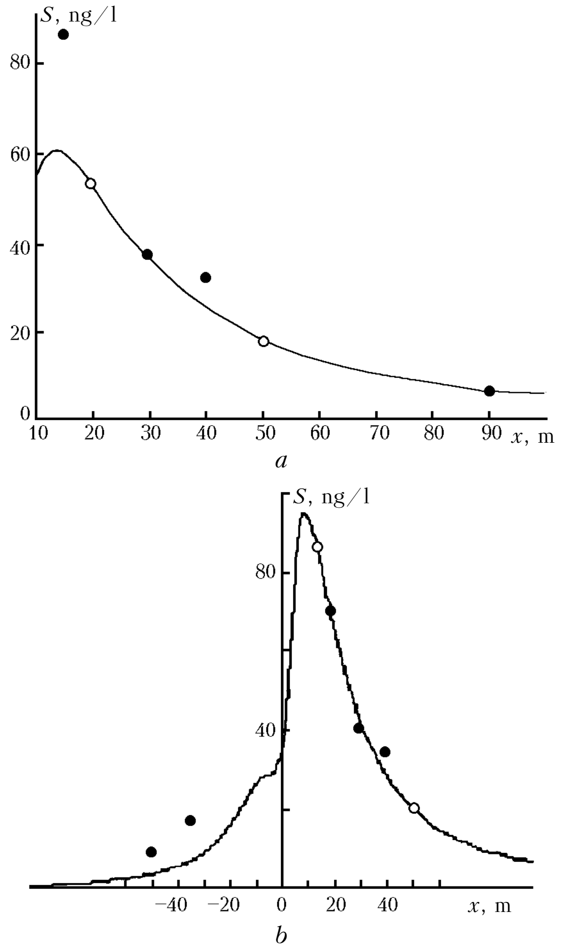

Fig. 3. Calculated and measured specific contents of benz(a)pyrene in the snow cover for Barnaul (*a*) and Sovetskoye (*b*) highways.

Table 2 demonstrates estimates of parameters for different PAH components. Analysis of the presented data shows a satisfactory agreement between the calculated and observational data. The curves are practically similar due to the coincidence of estimates of Θ_1 for both sets of experimental data.

Estimates of Θ are linearly connected with the power of the source. A comparison of estimates for both highways shows that the BP emission for both highways is comparable. Near highway, the level of BP content in the snow cover is about 100 ng/l that can have a detrimental effect on the health of population (the maximal permissible BP concentration in water is about 5 ng/l).

As compared with winter season of 1999–2000, the values of Θ_1 parameters a bit smaller in 2000/01 winter season. According to Eq. (11), this means that average size of aerosol particles containing PAH decreased. However, the total PAH emission does not change practically and remains sufficiently high relative to the winter season of 1998–1999 (Ref. 7).

Conclusion

The conducted complex study of pollution of snow cover and the atmospheric surface layer by motor transport emissions makes it possible to draw the following conclusions.

Based on analytical dependences (3) and (5), the models are proposed evaluating a single air pollution of the highway locality, as well as the areas of intense pollution are determined for different wind directions.

The numerical model of long-term pollution of some area by motor transport emissions is proposed allowing a reconstruction of aerosol impurity concentrations on each side of a road and recalculation of these concentrations for arbitrary orientation of the road relative to the parts of the world. This significantly extends the capabilities of interpretation of experimental investigations.

Testing of the model showed its satisfactory agreement with the PAH observational data and data on different lead fractions. Comparison of the PAH profiles reconstructed from the measurement data obtained for Sovetskoye and Barnaul highways shows that they well agree accurate to the scale factor connected with the magnitude of total emission.

Essential structural variations in aerosol emissions from motor transport as a result of the use of lead-free gasoline are supported by the analysis of data on snow pollution during winter season of 2000–2001. Taking into account the impact of motor transport emissions on the environment shows the necessity to extend theoretical and applied investigations on the problem as well as to create the optimal and economical schemes of monitoring, analysis, as well as development of efficient measures to decrease the detrimental effect.

Acknowledgments

This work was supported by the SB RAS Integration Project No. 64.

References

1. N.S. Burenin and I.I. Solomatina, Tr. Gl. Geofiz. Obs., is. 352, 191–199 (1975).
2. G. Detri, *The Atmosphere Must Be Clean* (Medicine, Moscow, 1973), 379 pp.
3. Yu.G. Feldman, *Hygienic Assessment of Motor Transport as a Pollution Source of the Atmosphere* (Medicine, Moscow, 1973), 379 pp.
4. N.S. Burenin, P.I. Onikul, and I.I. Solomatina, Tr. Gl. Geofiz. Obs., Is. 436, 102–110 (1979).
5. N.S. Burenin, Tr. Gl. Geofiz. Obs., Is. 467, 74–80 (1983).
6. V.F. Raputa, V.V. Kokovkin, O.V. Shuvaeva, and S.V. Morozov, Atmos. Oceanic Opt. **13**, No. 8, 733–737 (2000).
7. V.F. Raputa, V.V. Kokovkin, O.V. Shuvaeva, and S.V. Morozov, Atmos. Oceanic Opt. **14**, No. 3, 219–221 (2000).
8. V.P. Pchelintsev, in: *The Effect of Human Activities on the Environment of Komi ASSR* (Syktyvkar, 1982), pp. 103–114.
9. M.E. Berlyand, *Present-Day Problem of Atmospheric Diffusion and Pollution of the Atmosphere* (Gidrometeoizdat, Leningrad, 1975), 448 pp.
10. M.E. Berlyand, *Prediction and Control of Atmospheric Pollution* (Gidrometeoizdat, Leningrad, 1985), 272 pp.
11. V.V. Fedorov, *Theory of Optimal Experiment* (Nauka, Moscow, 1971), 312 pp.
12. A.I. Krylova, V.F. Raputa, and I.A. Sutorikhin, Meteorol. Gidrol., No. 5, 5–13 (1993).