Estimation of density of atmospheric admixture deposits in the urban snow cover

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Model calculations of the density of atmospheric admixture deposits in the urban snow cover are performed with the use of a semi-empirical equation of turbulent diffusion. Features of diurnal accumulation of an admixture on the surface under various weather conditions and source location are discussed.

Introduction

Snow is a natural accumulator of pollutants falling from the atmosphere onto the ground surface in winter. Earlier the content of harmful chemical constituents in snow coming from the atmosphere was studied in the State Scientific Center "Vektor" in order to evaluate the regional ecological situation. The R&D Center of Aerobiology deals, within the SB RAS Integration Project, with systematic investigation of biogenic pollution in snow cover of Novosibirsk.[1,2] In this connection, it is worth estimating the density of atmospheric admixture deposits in the urban snow cover using methods of mathematical simulation. For this purpose, we have formulated the following objectives:

1. To assess regularities in variation of the density of deposit accumulated during 24 hrs at the point with coordinates x and y depending on weather conditions, source height, and size of admixture particles.

2. To determine regularities in variation of the total amount of substance deposited during 24 hrs on the surface depending on the above conditions.

Earlier, using mathematical simulation of atmospheric admixture diffusion, we considered atmospheric air circulation over urban territories that led to the formation of "aerosol caps" above cities, under which the atmospheric admixtures are being accumulated and specifically transformed.[3,4] This paper uses the methods described in Refs. 3 and 4 and presents the analysis of model calculations of the density of atmospheric admixture deposits in the urban snow cover.

Technique and conditions of calculations

The admixture diffusion was calculated through numerical solution of a semi-empiric equation of turbulent diffusion[5]:

$$\frac{\partial \bar{C}}{\partial t}+\frac{\partial \bar{U}_i \bar{C}}{\partial x_i}-\frac{\partial}{\partial x_i}K_{ij}\frac{\partial \bar{C}}{\partial x_j}=\bar{Q} \quad (i,\, j=\overline{1,\,3}), \quad (1)$$

where $\bar{C}$ and $\bar{U}_i$ are mathematical expectations of the admixture concentration and wind velocity components; K_{ij} are the components of the tensor of turbulent diffusion coefficients (it was taken that $K_{ij}=0$ at $i \neq j$); $\bar{Q}$ is the term describing the sources of admixture; $x = x_1$ and $y = x_2$ correspond to the horizontal coordinates, and $z = x_3$ correspond to the vertical coordinate; t is time. The repeated subscripts mean summation. To take into account the gravitational sedimentation of the admixture particles, the particle sedimentation rate V_s was added to the z-component of the wind velocity.

The problem was solved in a rectangular parallelepiped G with the surface S comprising the side surface Σ, the base Σ_0 (at $z = 0$), and the top Σ_H (at $z = H$). The parallelepiped base was a 36×36 km square. A city was represented by a square (64 km^2) at the center of the rectangle Σ_0. The vertical coordinate of the computational domain was limited by the height H of the atmospheric boundary layer equal to 1.5 km. The system of the initial and boundary conditions for Eq. (1) is as follows:

$$\bar{C}(x,y,z,0)=0; \quad \bar{C}=0 \quad \text{at} \quad \Sigma,\ \Sigma_H;$$

$$-K_{zz}\frac{\partial \bar{C}}{\partial z}+V_s\bar{C}=\beta\bar{C} \quad \text{at} \quad \Sigma_0, \quad (2)$$

where β is the parameter of the admixture interaction with the surface. In calculations we took $\beta = 0.02$.

Before solving this semi-empirical equation, we determined the fields of mean wind velocity components. This problem was solved with the use of the numerical-analytical model considered in Ref. 6 in the following order. First, the diurnal behavior of the mean wind velocity components was determined in a 1-hour interval. These calculations were performed for the weather conditions typical of winter in Novosibirsk. Then, solving Eq. (1), we determined the fields of admixture concentration generated by a stationary point source and the density of its deposit on the surface. The term describing the source in Eq. (1) was specified as

$$\overline{Q}=Q_0\,\delta(x-x_0)\delta(y-y_0)\delta(z-z_0), \qquad (3)$$

where $Q_0 = 10^3$ g/s is the source emission rate; x_0, y_0, and z_0 are the source coordinates. The particle flux $p(x, y, t)$ onto the surface at the point with the coordinates x and y at the time t was determined as

$$p(x,y,t)=-V_s\overline{C}+K_{zz}\frac{\partial \overline{C}}{\partial z} \quad \text{at} \quad z = 0, \qquad (4)$$

and the deposit density accumulated for $T = 24$ h at the point with the coordinates x and y was calculated as

$$P(x, y)=\int_0^T p(x,y,t)\,\mathrm{d}t\,. \qquad (5)$$

The total amount of the substance deposited on the surface for 24 h $P_{\Sigma 0}$ was determined by integration of Eq. (5) over the area Σ_0. The calculations were performed for the following conditions. We considered two source locations: at the center of the city and 2 km far from the western boundary of the city at the height of 100 and 400 m. The following weather conditions were taken into account: calm and western wind with the speed of 2 m/s. Two sorts of admixture were considered with the particle diameters of 2 and 10 μm.

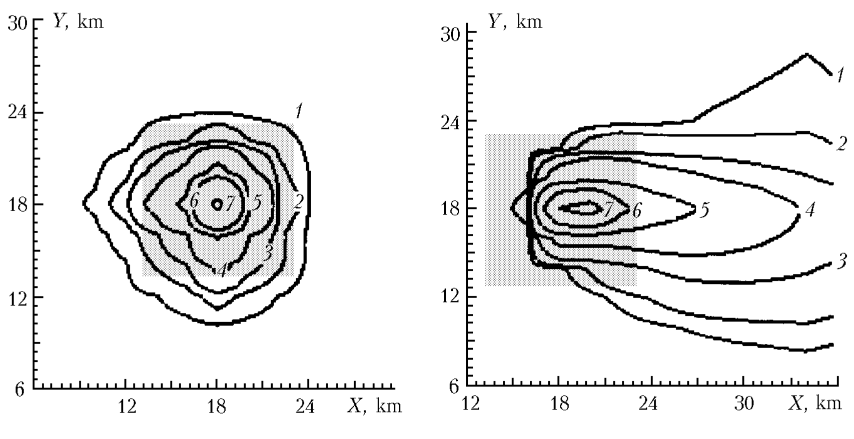
Analysis of calculated results

Tables 1 and 2 present the calculated results on the maximum values of $P(x, y)$ and $P_{\Sigma 0}$, respectively. When the source of admixture was located at the center of the city at the height of 100 m, the maximum value of $P(x, y)$ under calm weather conditions (see Table 1) was achieved near the source. The deposit density monotonically decreased from the city center to its periphery and almost vanished in suburbs (Fig. 1*a*). Such a behavior is characteristic of the admixture of both sorts.

In the presence of wind, the maximum value of the deposit density is halved (see Table 1), its position shifts by 2 km to the east from the city center. In this case, the deposit is distributed in the eastern part of the city, outskirts, and suburbs (Fig. 1*b*). The deposit density at the city center decreases 1.9 times as compared to that under calm situation. The particle diameter affects only weakly the value and the distribution of the main amount of admixture under varying weather conditions. In the presence of wind, the total amount of the substance deposited for 24 h onto the surface is 1.4 times larger than that under calm conditions (see Table 2).

Table 1. Calculated values of $P(x, y)$, in g/m^2

Particle diameter, μm	Source at the city center		Source outside the city	
	Weather conditions			
	calm	windy	calm	windy
	Source at the height of 100 m			
2	0.38	0.20	0.20	0.40
10	0.40	0.20	0.20	0.40
	Source at the height of 400 m			
2	0.065	0.020	0.030	0.030
10	0.073	0.020	0.038	0.030

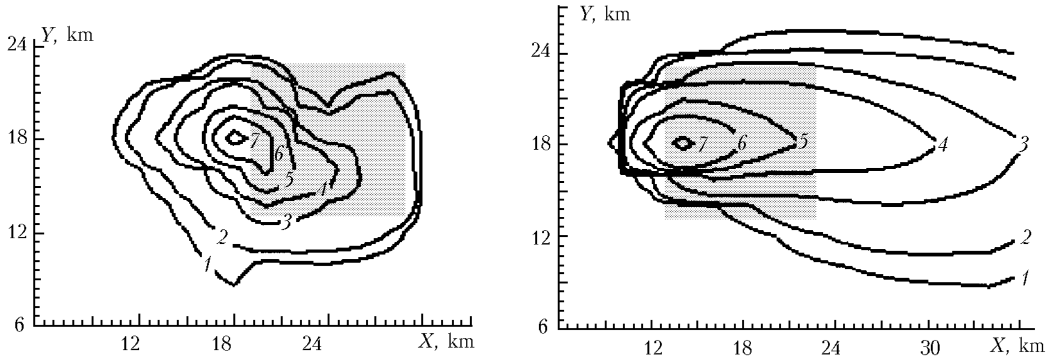


a *b*

Fig. 1. Isolines of $P(x, y)$ for the source located at the city center at 100-m height: calm (*a*) and windy (*b*) conditions. Source emission power of $0.4\cdot10^{-3}$ (*1*), $0.1\cdot10^{-2}$ (*2*), $0.4\cdot10^{-2}$ (*3*), $0.1\cdot10^{-1}$ (*4*), $0.4\cdot10^{-1}$ (*5*), 0.1 (*6*), 0.38 (*7, a*) and 0.2 g/m^2 (*7, b*); the city region is marked by gray color.

Table 2. Calculated values of $P_{\Sigma 0}$, g

Particle diameter, μm	Source at the city center		Source outside the city	
	Weather conditions			
	calm	windy	calm	windy
	Source at the height of 100 m			
2	5.17	7.08	4.13	9.92
10	6.22	7.57	5.03	10.5
	Source at the height of 400 m			
2	1.74	1.89	1.93	3.21
10	3.35	2.10	2.83	3.41



a *b*

Fig. 2. Isolines of $P(x, y)$ for the source located in the city suburbs at the height of 100 m: calm (*a*) and windy (*b*) conditions. Source emission power of $0.4{\cdot}10^{-3}$ (*1*), $0.1{\cdot}10^{-2}$ (*2*), $0.4{\cdot}10^{-2}$ (*3*), $0.1{\cdot}10^{-1}$ (*4*), $0.4{\cdot}10^{-1}$ (*5*), $0.1{\cdot}10^{0}$ (*6*), $0.38{\cdot}10^{0}$ (*7*, *a*) and $0.2{\cdot}10^{0}$ g/m^2 (*7*, *b*); the city region is marked by gray color.

When the source of admixture is located 2 km far from the western city boundary at the height of 100 m under calm conditions, the maximum value of the deposit density is observed beyond the city near the source (see Fig. 2*a* and Table 1). The deposit is distributed in the western outskirts and in the most part of the city territory.

At the same source location but in the presence of wind, the maximum value of the deposit density doubles and shifts toward the city by 2 km. The deposit is observed at western outskirts, almost everywhere in the city, and even in its eastern outskirts (see Fig. 2*b* and Table 1). The deposit density at the center of the city is an order of magnitude larger that that observed under calm conditions. The value and the distribution of the deposit density are almost independent of the particle diameter. As the wind speed increases up to 2 m/s, the amount of admixture deposited for 24 h exceeds that under calm conditions by more than two times (see Table 2).

Figure 3 shows an example of the time dependence of the total amount of substance deposited on the surface $P_{\Sigma 0}$ during a day under calm conditions for the source located at the height of 100 m. We can see that $P_{\Sigma 0}$ changes more sharply in daytime. This corresponds to the highest intensity of turbulent mixing that is observed in daytime.

In general, the results calculated for all the conditions considered demonstrate similar diurnal dynamics of the amount of substance deposited on the surface.

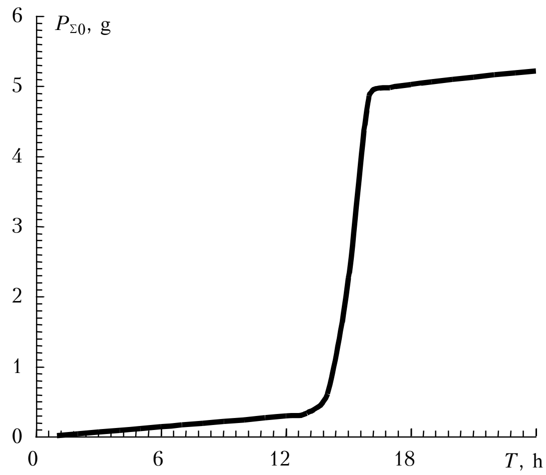


Fig. 3. Time dependence of $P_{\Sigma 0}$ under calm conditions for the source located at the height of 100 m.

Consider now the results obtained for the source located at the height of 400 m. If the source is located at the center of the city and under different weather conditions, the maximum value of the deposit density and the total amount of the deposited admixture vary, but the qualitative pattern remains the same as for the source at the height of 100 m. Thus, in the presence of wind, the maximum value of the deposit density decreases three times. If the source is located 2 km far from the western city boundary, the maximum of the deposit density almost does not change in the presence of wind (see Table 1).

Table 3. Ratio of $P_{\Sigma 0}$ for the source located at the height of 100 m to that for the source located at the height of 400 m

Particle diameter, μm	Source at the city center		Source outside the city	
	Weather conditions			
	calm	windy	calm	windy
2	2.97	3.75	2.14	3.09
10	1.86	3.6	1.78	3.08

On the whole, the maximum deposit density at the source located at the height of 400 m is five to six times smaller than that for the source located at the height of 100 m. This fact can be explained by higher atmospheric turbulence. The amount of admixture deposited on the surface for 24 h decreases two to three times as the source height increases from 100 to 400 m (Table 3).

Analysis of the results calculated shows that as the wind speed increases, the maximum amount of the deposited substance shifts toward the eastern suburb if the source is located at the center of the city and toward the city center if the source is located 2 km far from the western city boundary.

Thus, it can be concluded that the maximum values of the deposit density and the amount of the admixture deposited onto the surface for 24 h decrease markedly, as the source height increases. Weather conditions also have a considerable effect on the admixture diffusion.

Conclusions

In this work, the technique for calculation of the surface deposit density generated by sources located in a city or its suburbs has been developed based on some model situations. A cycle of calculations has been conducted in order to assess the structure of aerosol deposits under weather conditions typical of winter in Novosibirsk. Thus, the methodic basis has been prepared for research into regularities of accumulation of protein and living microorganisms in snow. In future, we plan to generalize the calculations for the whole winter period and to assess particular sources of admixture using measurement data and the methods of solution of inverse problems on the dispersal of atmospheric pollution.[7]

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