Analysis of aerosol pollution processes in the vicinity of the Irkutsk aluminum plant

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Abstract. The issues of assessing the pollution fields in the vicinity of industrial enterprises are discussed according to the monitoring studies of the snow cover. The formulations of problems of low-parameter reconstruction of concentration fields are considered on the basis of model descriptions of the processes of transport of impurities in the surface layer of the atmosphere. With regard to the Irkutsk aluminum plant, the results of studies of the pollution of its surroundings with aluminum are presented. Using the data of route observations, a numerical reconstruction of the fluoride content in the snow cover was carried out. The quality control of the results obtained is carried out by comparing the measured and calculated concentrations of impurities at the control points of observation.

1. Introduction

The production of aluminum in the world is constantly growing, as this element is widely used in various industries. In the process of electrolysis, aluminum is deposited in special electrolysis tanks with the release of associated impurities into the atmosphere. As a rule, aluminum is used in the composition of alloys with other chemical elements that increase their hardness, density, thermal conductivity, etc. Aluminum companion elements - F, Be, Li, B and others - are highly toxic. Specific diseases of the population are associated with them. Many water-soluble inorganic aluminum compounds are retained for a long time. They can have a harmful effect on the environment and public health. This has been proven by geochemical and hygienic studies in urbanized areas [1 - 6].

Snow cover is an informative and depositing component of the environment. In Siberia, the snow cover accumulates within 4-6 months and is a natural concentrator of many chemical elements. Its elemental composition testifies to the geochemical features of the territory associated with the specifics of the existing industrial production. Snow cover is the object of close attention of Russian [3, 4, 7 - 9] and foreign researchers [10 - 12] when assessing the ecological and geochemical state of the environment.

The use of methods for direct modeling of the transport of pollutants, in principle, makes it possible to describe the concentration fields quite correctly, but in this case this approach encounters limited possibilities of providing the models with the corresponding input information. These include uncertainties in specifying the power and height of the source, distribution in the initial cloud of aerosol particles by size and settling rate, determination of current meteorological conditions, etc. reconstruction
models [13, 14]. When using the formulations of inverse problems, it is undesirable to describe too detailed the processes of impurity transfer, since this can lead to significant difficulties in their substantiation and numerical implementation.

The aim of the work is to assess the fields of atmospheric pollution in the vicinity of the aluminum smelter using specialized ecological and geochemical studies of the composition of snow water, solid sediment in snow and model descriptions of the processes of transport of impurities in the surface layer of the atmosphere.

2. Objects and methods of research
The Irkutsk Aluminum Smelter (IrkAZ) is located on the territory of Shelekhov. Investigations of the pollution of its surroundings are given close attention; there is extensive information on the chemical state of the surrounding components, including the snow cover [4 - 6, 9, 15 - 17]. The industrial profile of the city is determined by non-ferrous metallurgy (IrkAZ and the cable plant), heat and power engineering and the production of building materials.

The snow sampling scheme is shown in figure 1. The weight of the snow samples reached 10 - 15 kg. The sampling area of each point ranged from 30x30 cm to 70x70 cm, depending on the depth of the snow layer. When processing the samples, the snow water was filtered (blue ribbon filter, pore diameter 1-2.5 microns) and the solid sediment was separated from the snow water phase in order to minimize the process of dissolution of technogenic dust from the solid snow sediment.

![Figure 1. Snow sampling scheme. Schematic map of the distribution of aluminum concentrations in snow water (A) and in solid snow sediment (B) in the zone of influence of emissions from IrkAZ.](image-url)
The determination of the elemental composition of snow water was carried out by mass spectrometry with inductively coupled plasma. For the analysis of the remaining ions, the following methods were used: mercurimetric - for the determination of chlorine-ion, turbidimetric for sulfate-ion, potentiometric - for fluorine-ion.

For the analysis of samples of solid snow sediment, arc atomic emission spectrometry with photoelectric recording and computer processing of spectra was used. The macro- and microelement composition of the solid snow sediment, including Al, was determined by the method of complete evaporation from the channel of the graphite electrode. Determination of fluorine in solid snow sediment was carried out by the method of arc atomic emission analysis.

The calculation of the average concentration of impurities in the surface layer of the atmosphere is focused on the so-called normal meteorological conditions. For them, a power-law approximation of the wind speed and the coefficient of vertical turbulent exchange is admissible [18, 19]:

$$u(z) = u_1 \left( \frac{Z}{Z_1} \right)^n, \quad K_z = k_1 \frac{Z}{Z_1},$$

where $u_1$ and $k_1$ are the values of $u$ and $K_z$ at $z = Z_1$.

Then, in the case of a point source, we obtain the following expression [20]

$$\bar{q}(r, \varphi) = \int_{\Omega} q(r, \varphi, k_1, u_1) \cdot p_1(k_1, u_1) dk_1 du_1,$$

where $(r, \varphi)$ are the polar coordinates, $p_1(k_1, u_1)$ are joint probability density $u_1$ and $k_1$ over the averaging period, $\Omega$ – is the area of real change $u_1$ and $k_1$,

$$q(r, \varphi, k_1, u_1) = P(\varphi + 180^\circ) \cdot \frac{Q \lambda}{r}.$$  

Here $P(\varphi)$ is the surface wind rose, $\lambda$ - is a one-time concentration for a linear source.

For a light impurity, the function $q(r, \varphi, k_1, u_1)$ is represented as

$$q_\lambda = \frac{Q}{(1 + n) k_1 r \varphi_0 \sqrt{2\pi}} \cdot e^{-\frac{u_1 H^{1+n}}{k_1 (1+n)^2}},$$

Here $Q, H$ are the emission value and effective source height, $\varphi_0$ is the wind speed dispersion.

From the climatological analysis of observational data on the network of heat balance stations, it follows the possibility of presenting [20]

$$p_1(K_1, u_1) = p'(u_1) \cdot p''(\lambda), \quad \lambda = \frac{k_1}{u_1}. $$

As a first approximation, we can take

$$p''(\lambda) = \delta(\lambda - \lambda_0), \quad \delta(\lambda) - is the delta function.$$  

In the case of a light impurity, taking into account (3) - (6), from relation (2) it follows

$$\bar{q}(r, \varphi) = \frac{Q P(\varphi + 180^\circ)}{\sqrt{2\pi} \varphi_0 r^2} \cdot \int_{\Omega_1} \frac{\frac{\lambda}{u_1} \cdot p'(u_1) \cdot p''(\lambda) - \frac{H^{1+n}}{e^{\lambda(1+n)^2}}} {n + 1} d\lambda du_1 =$$

$$= \frac{Q P(\varphi + 180^\circ) \lambda}{\sqrt{2\pi} (1 + n) \varphi_0 r^2} \cdot \frac{e^{-\frac{H^{1+n}}{\lambda(1+n)^2}}} {\sqrt{2\pi} \varphi_0 r^2} \cdot \int_{0}^{u} p'(u_1) du_1 =$$

$$= Q_1 P(\varphi + 180^\circ) \lambda e^{-\frac{\theta_1}{r^2}},$$

$$\theta_1 = \frac{Q \lambda}{\sqrt{2\pi} (1 + n) \varphi_0} \cdot \int_{0}^{u} p'(u_1) du_1, \quad \theta_2 = \frac{H^{1+n}}{\lambda(1+n)^2}.$$  

Aggregated parameters $\theta_1, \theta_2$ are estimated from observational data using the least squares method [21].
Approbation of the estimation model was carried out on the monitoring data of snow cover pollution with fluorine in the vicinity of IrkAZ [16, 17]. Table 1 shows the results of measurements of the fluorine content in snowmelt water at the end of the winter seasons of 1996 and 2015.

| The direction and year of snow sampling | Distance from the plant |
|----------------------------------------|-------------------------|
|                                        | 0.5 km | 1 km | 2 km | 6 km |
| Southeast, 1996                       | 39     | 37.5 | 14   | 7.3  |
| Northeast, 1996                       | 55     | 52   | 17.5 | 2.4  |
| Northwest, 1996                       | 52     | 34   | 19.5 | 5    |
| Southeast, 2015                       | 60     | 52   | 18   | 2.4  |

3. Results and discussions
In the city of Shelekhov, the dust content of snow varies in a wide range and reaches 70 g / m$^2$. Lower dustiness is observed on the outskirts of the city. For comparison, the dust content of snow on Lake Baikal (Mandarkhan Bay) is only 1 g / m$^2$ or less. The content of macrocomponents is in the range of 11-95 mg / L. Near the aluminum smelter, the content of F ion in 2008-2012 reached 25 mg / L, which is almost 600 times higher than the local natural background on Lake Baikal - 0.05-0.09 mg / L [15].

In figure 1 shows the levels of high, medium and relatively low aluminum content in the vicinity of IrkAZ based on the results of monitoring the pollution of the snow cover. Analysis of figure 1A shows that the dynamics of the spatial change in the concentration of aluminum in the snow melted water is quite significant. Figure 1B it can be seen that the field of aluminum concentration in solid snow sediment changes more smoothly with distance from the industrial site of the plant.

Between snow water and solid snow sediment within the city and its surroundings (3-5 km) for many toxic elements, there is a conjugation of compositions, when an increase or decrease in the content of an element is noted simultaneously in snow water and solid snow sediment. This is usually traced for the main pollutants of industrial cities, in particular, such a correlation in Shelekhov is clearly observed between the Al contents in the same places of sampling and analysis of snow water and solid sediment samples.

From a preliminary analysis of the data in table 1 that the maximum concentration of fluorides is reached at distances of less than one kilometer, which indicates a relatively small height of impurity emissions within a few tens of meters. This leads to a rather rapid decrease in their concentration with distance from the plant. When comparing the dynamics of the decrease in fluorine concentrations with distance for different directions, a certain similarity is observed, which indicates a rather successful choice of the effective center of impurity ejection. Taking into account the relatively small height of the impurity ejection, it should also be noted that the observation points are located close to optimal on the sampling routes - their concentration in the immediate vicinity of the source and gradual discharge as they move away.

Linear configurations of smoke emission sources are typical for aluminum smelters. This requires certain adjustments in the use of models and methods for analyzing monitoring data. Taking into account the conclusions of the preliminary analysis of the experimental data, it follows that such an adjustment is already contained in the corresponding location of the snow monitoring system in the vicinity of the IrkAZ industrial site.

In figure 2 shows the results of the numerical reconstruction of fluoride concentrations in snow melted water for various radial sampling routes. Snow sampling was carried out according to the system of key sites, taking into account the sources of atmospheric pollution and the wind rose. Sampling routes radial relative to the plant were used with offsets of 0.5, 1, 2 and 6 km in the north-east, north-west,
south-east and south-west directions. The recovery of fluorine concentrations along the sampling routes was carried out on the basis of a light impurity model using relation (7).

Observation points at distances of 0.5 and 2 km from the plant were taken as reference points for all directions. In general, there is some agreement between calculations and observations. The \( r_{\text{max}} \) estimates in all cases turned out to be close to the distance of 0.6 km from the plant. \( r_{\text{max}} \) is the distance at which the maximum surface concentration is reached.

![Graphs showing fluoride concentrations in different directions](image)

**Figure 2.** Measured and numerically reduced fluoride contents in the directions: northwest from IrkAZ for the winter season 1996 (a) and in the direction from the plant to the southeast for the winter season 2015 (b). ●● are the reference and control points of measurements, _____ are the simulation results.

The proposed model makes it possible to trace the spatial variability of fluorine concentrations depending on the distance and direction from IrkAZ in winter. High levels of fluoride pollution spread to residential areas, farmland and horticultural cooperatives. The area near IrkAZ (up to 1 km) is most intensively polluted by man-made emissions. With the distance from the plant (from 2 to 6 km), a fairly rapid decrease in fluorine concentrations occurs. Having recalculated the fluorine content in the snow (mg/dm\(^3\) or mg/L) into areal indicators (mg/m\(^2\)), using the developed model, it is possible to control the total emissions of the enterprise for a long period of time using limited experimental information. In figure 3a shows the fluoride concentration field reconstructed on the basis of model (7).
To estimate the parameters, the data of snow monitoring in 2015 in the vicinity of IrkAZ were used. To obtain a spatial picture of fluoride deposition, the average climatic winter wind rose for the city of Shelekhov was used (figure 3b, source: https://world-weather.ru/archive).

Analysis of figure 3a, it follows that in the winter period, the main foci of pollution are formed in the southeastern and northwestern directions of fluoride removal from emission sources. This is quite consistent with the winter frequency of winds. The maxima of impurity deposition are located at relatively small distances from the industrial site of the plant.

4. Conclusion
Currently, the main pollutants in Shelekhov are the following toxicant elements - Al, Be, F, Li, B, to a lesser extent - Ni, Co, Cd, Mo, As, V, Cu, S. Their prolonged intake leads to pollution atmosphere, water, soil and vegetation layer of the surrounding area and excludes the possibility of population living in such places.

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