Assessment of the effect of regional industrial atmospheric pollution on Lake Baikal

V.K. Arguchintsev, A.V. Arguchintseva, and M.A. Kreisik

Irkutsk State University

Received November 29, 2000

The effect of regional industrial enterprises on pollution of the atmosphere and water surface of Lake Baikal is assessed based on the mathematical models proposed by the authors.

Introduction

Lake Baikal is now an object of particular attention of scientists, government, and population. The world community is solicitous about preservation of its biological diversity and uniqueness. Therefore, to take optimal measures, it is necessary to know the loads on the lake and neighboring territories due to anthropogenic impact. It should be noted that the history of the human society knows a lot of examples that its following sustainable development depended on successful solution of arising problems.

Large industrial enterprises are concentrated in the south of the Irkutsk Region, mostly in the valley of the Angara River, as well as directly on the Baikal lakeside. Thus, for example, according to the data of the last inventory, there are 156 objects only in Irkutsk, which include 3267 various sources emitting 117 ingredients into the urban atmosphere. The valley of the Angara River is oriented so that it favors the directed transport of pollutants by prevailing northwestern winds in the atmospheric boundary layer. A significant role in the processes of pollution spread is played by climatic peculiarities of the Eastern Siberia, namely, the continental climate, high repetition of calm situations and near-surface and elevated inversions, especially in cold seasons, as well as low precipitation. All these factors favor accumulation of high concentrations of ingredients and aerosol particles in the immediate vicinity of their sources.

1. Analysis of long-term series of meteorological characteristics of the region under study

Processing of long-term observations of meteorological stations and posts near the Angara River allowed us to present the atmospheric potential for self-cleaning in large industrial centers in the form of climatic ellipses of concentration. For illustration, the concentration ellipses for December and April are shown in Fig. 1.

In the Eastern Siberia the weather in December is characterized by a stable Asian anticyclone. Its features are high atmospheric pressure and near-surface and elevated inversions in combination with weak winds. At this period, pollutants from elevated sources are mostly concentrated near their sources, forming a high pollution potential of the atmosphere. However, in the Southern Baikal Region, winds with a strong monsoon component arise because of large temperature differences between the water surface and the land. These winds provide transport of pollutants emitted by industrial enterprises of Baikal'sk, Kultuk, and Slyudyanka toward Baikal, and different pollution fields can superimpose (see Fig. 1).

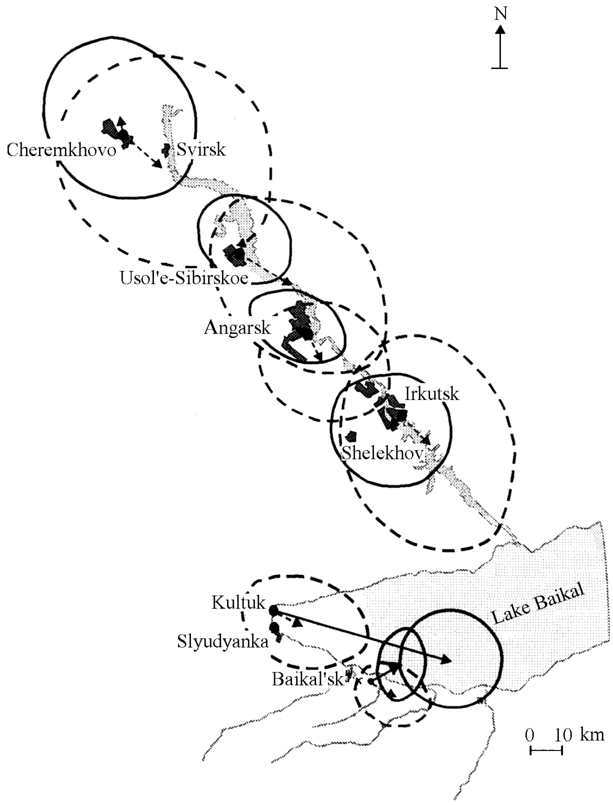

Fig. 1. Climatic concentration ellipses of the wind flow and resulting vectors of wind velocity (1 m/s corresponds to 10 mm) for April (dashed line) and December (solid line).

As the income of solar radiation increases late in winter, the Asian anticyclone gradually breaks down, and the wind speed increases markedly, reaching its

0235-6880/01/03 216-03 $02.00

highest values in April–May. In this period, the anthropogenic pollutants are transported by airflows to longer distances. As a result, pollution fields produced by different enterprises overlap (see Fig. 1). At the same time, the level of pollution near emission sources decreases as compared to winter months. In the Southern Baikal Region, the wind weakens, and pollutants localize near their local sources. It should be noted that for this region December and April can be considered as representatives of a year, because they characterize different conditions of the pollution dispersion.

The concentration ellipses give a qualitative pattern of the atmospheric capability to self-cleaning and help us to restrict our calculations to individual situations. The actual pollution pattern can be naturally obtained only when considering in detail both meteorological conditions and parameters of emission sources.

2. Mathematical simulation of zones of dangerous pollutant concentrations

To characterize quantitatively the frequency of excess over standard concentrations of various ingredients in the atmospheric surface layer, we conducted numerical experiments based on the Fokker–Planck–Kolmogorov equation written in the phase coordinate of concentration s:

$$\frac{\partial p}{\partial t} + \frac{\partial [A(t, s)p]}{\partial s} = \frac{\partial^2 [B(t, s)p]}{\partial s^2}. \qquad (1)$$

Here $p = p(t, s)$ is the differential distribution law for s; $A = \frac{\partial \bar{s}}{\partial t}$ and $B = \frac{1}{2}\frac{\partial \overline{s'^2}}{\partial t}$ are, respectively, the mean rate of change of the mean concentration $\bar{s}$ and the intensity of fluctuations near this mean in the interval $t \in [0, T]$.

The initial state is $p(0, s) = p_0(s)$. The boundary conditions are

$$\frac{\partial (Bp)}{\partial s} - Ap = 0 \ \text{ at } \ s \to \infty, \ \text{ and } \ \int_0^\infty p(t, s)\mathrm{d}s = 1.$$

Following Refs. 1–3:

$$A = \frac{\partial \bar{s}}{\partial t} = -\frac{\partial \bar{u}_i \bar{s}}{\partial x_i} + \frac{\partial w_g \bar{s}}{\partial x_3} - \alpha \bar{s} + \bar{F} + \frac{\partial}{\partial x_i}\left(K_{ij}^{(1)}\frac{\partial \bar{s}}{\partial x_j} - F^{(1)}\right) + \frac{\partial}{\partial x_i}\bar{k}_{ij}\frac{\partial \bar{s}}{\partial x_j}; \qquad (2)$$

$$B = K_{ki}^{(1)}\left(\frac{\partial \bar{s}}{\partial x_i}\right)^2;$$

$$K_{ki}^{(1)} = \frac{1}{T-\tau}\int_0^{T-\tau} u'_k(t+\tau)\int_t^{t+\tau} u'_i(t_1)\,\mathrm{d}t_1\,\mathrm{d}t;$$

$$F^{(1)} = \frac{1}{T-\tau}\int_0^{T-\tau} u'_k(t+\tau)\int_t^{t+\tau} F'(t_1)\,\mathrm{d}t_1\,\mathrm{d}t;$$

u' and F' are, respectively, fluctuations of the speed and intensities of sources; τ is the Eulerian scale.

Statistical processing, including calculation of correlation functions, was performed with the data of long-term observations at the stations Zima, Zalari, Cheremkhovo,* Kutulik, Usol'e-Sibirskoe,* Angarsk,* Irkutsk,* Uchkhoz "Molodezhnyi" (Irkutsk), Shelekhov,* Patrony, Istok Angary, Kultuk, Slyudyanka,* Vydrino, Baikal'sk,* and Tankhoi. Towns, whose industrial emissions into the atmosphere were taken into account in the model, are marked by asterisk.

The values of wind velocity components at nodes of a regular grid were determined by the method of optimal interpolation, whose error does not exceed variances of a random function on the assumption that measurement errors at different cross sections do not correlate with each other and with actual values of the functions.[4]

The field of vertical speeds was determined by integrating the continuity equation

$$\frac{\partial \rho_b u}{\partial x} + \frac{\partial \rho_b v}{\partial y} + \frac{\partial \rho_b w}{\partial z} = 0$$

over height

$$w_z = -\frac{1}{\rho_b}\int_0^z \rho_b\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\mathrm{d}z,$$

where ρ_b is the background density, which is constant along the horizontal and varies with height.

Equations (1)–(2) with the corresponding boundary conditions were solved numerically based the splitting method.[5]

For discretization in time, we used the dicyclic method of multicomponent splitting with the Crank–Nicholson scheme at every fractional step.[6] For preservation of the properties of monotonicity and positiveness, regularization by the Samarskii scheme was carried out.[7] In numerical realization of finite-difference equations, nonmonotonic sweep was used.[8]

The constructed finite-difference schemes are stable and have the second order of approximation in time and coordinates.

When modeling the processes, we considered the integration domain with the area 400×250 km^2 and height of 2 km above the surface. The horizontal step was 1000 m, and the vertical step was variable:

10 m at $z < 50$ m,
50 m at $50 < z \le 150$ m,
150 m at $150 < z \le 300$ m,
200 m at $300 < z \le 500$ m,
500 m at $z > 500$ m.

We present the calculated frequencies of excess over the mean diurnal maximum permissible concentration (MPC) for sulfur oxide (IV) in April (Fig. 2) and December (Fig. 3). In the figures, isoline *1* contours the area, in which zones dangerous from the viewpoint of violation of the above criterion arise no less than 24 h per month.

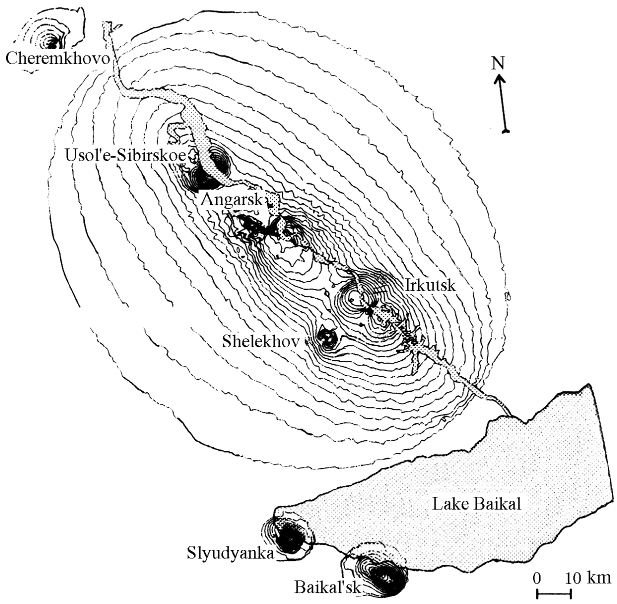

Fig. 2. Frequency of exceeding MPC = 0.05 mg/m^3 for sulfur oxide (IV) in April. The isoline step is 24 h.

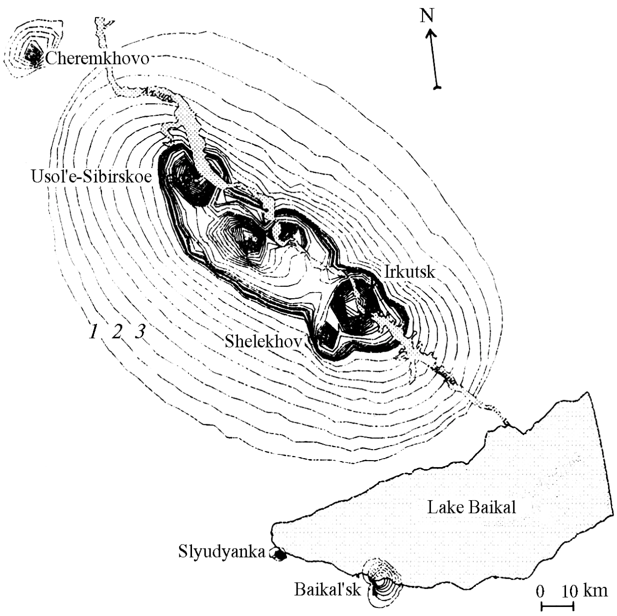

Fig. 3. Frequency of exceeding MPC = 0.05 mg/m^3 for sulfur oxide (IV) in December. The isoline step is 24 h.

The repetition of northwestern winds is high in the region near the Angara River in April (see Fig. 2). This leads to rapid dispersion of pollutants. Pollutants are transported to long-range distances, and their concentration decreases fast. So the concentrations at the Baikal boundaries are less than MPC. However, calm situations prevail on Baikal itself in this season. The calm weather favors appearance of dangerous zones in the immediate vicinity of pollution sources. In December (see Fig. 3) weak winds prevail in the region near the Angara River, and repetition of dangerous concentrations increases sharply. Detailed calculations show that the pollutant concentrations near some sources may 10–20 times exceed MPC. This month, rather strong local winds arise because of large temperature differences between the land and water. The winds rapidly transport pollutants to large distances. As a result, the pollutant concentrations near some sources either do not exceed MPC (see Fig. 3, Slyudyanka) or exceed it by no more than 1 MPC only in the immediate vicinity of the sources (see Fig. 3, Baikal'sk).

3. Conclusions and prospects

Consideration of climatic characteristics and their fluctuations for a particular territory gives such an integral characteristic as repetition of dangerous (from the viewpoint of formulated criteria) concentrations for the considered period. Just the prolonged exposure of living organisms to the action of the increased concentration of some ingredients determines various functional derangements. It is also interesting to elaborate the limits of MPC violation for vegetation of the reserved territories like Lake Baikal. Unfortunately, now there are no clearly developed criteria of protection of such territories in Russia (except for the territory of Yasnaya Polyana).

Acknowledgments

This work was partially supported by the Russian Foundation for Basic Research (Projects No. 98–05–64020 and No. 98–05–64021) and the Ministry of Education of the Russian Federation (Grant No. 97–0–13.3–12).

References

1. A.V. Arguchintseva, Atmos. Oceanic Opt. **11**, No. 6, 524–527 (1998).
2. A.V. Arguchintseva, Atmos. Oceanic Opt. **12**, No. 6, 480–483 (1999).
3. A.V. Arguchintseva, Atmos. Oceanic Opt. **13**, No. 9, 804–809 (2000).
4. L.S. Gandin and R.L. Kagan, *Statistical Methods for Interpretation of Meteorological Data* (Gidrometeoizdat, Leningrad, 1976), 359 pp.
5. V.K. Arguchintsev, Atmos. Oceanic Opt. **7**, No. 8, 594–596 (1994).
6. G.I. Marchuk, *Methods of Computational Mathematics* (Nauka, Moscow, 1989), 608 pp.
7. V.M. Paskonov, V.I. Polezhaev, and L.A. Chudov, *Numerical Simulation of Processes of Heat and Mass Exchange* (Nauka, Moscow, 1984), 288 pp.
8. A.A. Samarskii and E.S. Nikolaev, *Methods for Solution of Grid Equations* (Nauka, Moscow, 1978), 592 pp.