Simulation of the spreading of hydrocarbons in the atmospheric boundary layer above the Southern Baikal region

V.K. Arguchintsev and V.L. Makukhin

Limnological Institute,
Siberian Branch of the Russian Academy of Sciences, Irkutsk
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Based on a three-dimensional nonlinear nonstationary model of the spreading and transformation of admixtures, numerical experiments have been performed on the transport and diffusion of total hydrocarbons from vehicles and enterprises of the Irkutsk–Cheremkhovo industrial complex, Slyudyanka, Baikal'sk, Selenginsk, Ulan-Ude, and Gusinoozersk.

The necessity of studying the spreading of hydrocarbons emitted by industrial enterprises is caused by their adverse effect on the population and environment. Many hydrocarbons breathed with air produce toxic, carcinogenic, mutagenic, teratogenic, and allergic effects.[1,2]

Instrumental measurements of the distribution of separate hydrocarbons in the region of Lake Baikal have been started only recently. In Ref 3, based on the data of snow cover pollution with polyaromatic hydrocarbons in the Irkutsk environs, the rate of their accumulation was analyzed as a function of the climatic parameters, in particular, the recurrence of wind directions at altitudes above 100 m.

The experimental technique used in the present paper – a mathematical simulation – has allowed us to obtain the information on spatial fields of total hydrocarbon concentrations in the atmosphere over the Southern Baikal region, to calculate eddy fluxes of pollutants in the atmospheric layer above the water surface, and to estimate the contribution of emissions of groups of enterprises to the pollution of the lake. In numerical calculations, a three-dimensional nonlinear nonstationary model of the spreading and transformation of admixtures[4] was used. The spreading of hydrocarbons from stationary sources and vehicles was considered. Emissions of the enterprises of the Irkutsk–Cheremkhovo industrial complex, Slyudyanka, Baikal'sk, Ulan-Ude, Selenginsk, and Gusinoozersk were taken into account. The total strengths of emission sources, borrowed from Ref. 5, are given in Table 1.

The spreading of admixtures was simulated in the region with an area of 500×250 km and an altitude of 3 km above the Lake Baikal surface. The relief of the examined region was taken from the 1:100 000 topographical maps. Time and horizontal increments were 150 s and 5 km, respectively; vertical increments were as follows:

$$\Delta z = \begin{cases} 20 \text{ m} & \text{for } z \le 200 \text{ m} \\ 300 & 200 < z \le 500 \\ 500 & 500 < z \le 1000 \\ 1000 & z > 1000. \end{cases}$$

The turbulent diffusion coefficients were calculated with the use of the formulas of the semi-empirical theory of turbulence.[6]

Table 1. Parameters of the sources of hydrocarbon emissions for the Southern Baikal region.

Emission source	Strength, g/s
Cheremkhovo	13
Usol'e-Sibirskoe	41
Angarsk	1524
Shelekhov	13
Irkutsk	142
Slyudyanka	6
Baikal'sk	6
Selenginsk	35
Gusinoozersk	16
Ulan-Ude	108

Numerical experiments were carried out for spring and winter, represented by December and April.[7] Meteorological situation in December is characterized by the stationary Siberian anticyclone, with still and windless weather in the Angara valley and winds with strong monsoon component that have their origin in the Southern Baikal region and blow from land toward the lake.

In Fig. 1 the contour lines are shown of the field of calculated surface concentrations of hydrocarbons in December. A small-gradient baric field hinders the removal of pollutants through the Angara valley toward Lake Baikal, and the admixtures are mainly concentrated near the industrial centers. Eddy fluxes of hydrocarbons toward the water surface of the lake are most intense in the regions of Slyudyanka and Baikal'sk and reach 500–650 μg/(m^2·day) (see Table 2). In the atmospheric layer above the water surface, the eddy fluxes of hydrocarbons, emitted by the enterprises and vehicles of Selenginsk, are much less intense [80–110 μg/(m^2·day)], because the emission sources are far from Lake Baikal. The average eddy flux intensity in the atmospheric layer above the water surface was 70.5 μg/(m^2·day) for an area of 9000 km^2.

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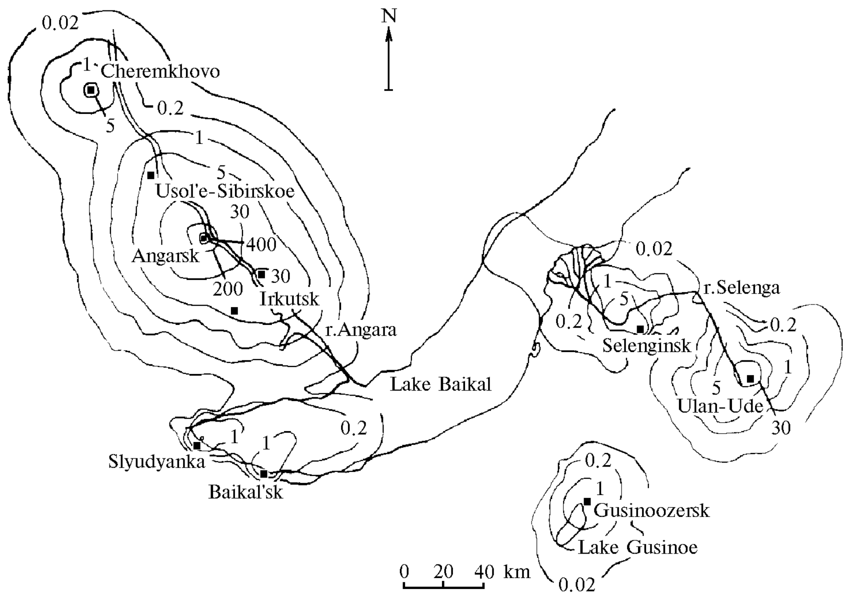

Fig. 1. Contour lines of the calculated surface concentrations of hydrocarbons in December, in μg/m^3.

Table 2. Calculated intensities of eddy fluxes of hydrocarbons toward the water surface of Lake Baikal, in μg/(m^2·day), in December and April.

Group of enterprises	Eddy flux intensities for the indicated regions of the lake					
1	2	3	4	5	6	7
			December			
All sources	314–651	42–232	10–11	67–105	0.7–3.3	70.5
IC	<0.01	<0.01	1.1–1.2	<0.01	<0.01	0.1
SU	<0.01	<0.01	<0.01	67–105	<0.01	14.8
SB	314–651	42–232	9–10	<0.01	0.7–3.3	55.6
			April			
All sources	1108–1962	1064–2199	2–5	170–414	0.9–2.8	147.8
IC	0.01	0.03–0.1	0.7–1.4	<0.01	<0.01	0.1
SU	<0.01	<0.01	<0.01	170–414	<0.01	27.5
SB	1108–1962	1064–2199	1.2–3.2	<0.01	0.9–2.8	120.2

To estimate contributions of emissions of each group of enterprises (Irkutsk–Cheremkhovo industrial complex, Slyudyanka and Baikal'sk, and Selenginsk and Ulan-Ude) to the pollution of the lake, we carried out model calculations for the emission sources of these industrial complexes separately and calculated eddy fluxes above the lake surface. The results of calculations are given in Table 2.

In the first column of Table 2 the groups of emission sources are named, where IC is for the Irkutsk–Cheremkhovo industrial complex, SU is for the industrial complexes of Selenginsk and Ulan-Ude, and SB is for the enterprises and vehicles of Slyudyanka and Baikal'sk, put in operation provided that the remaining groups do not emit admixtures at the given time period. Columns 2 to 6 contain the calculated eddy flux intensities in the atmospheric layer above the water surface of the lake in the following regions: in the second column for the region located at distances of 5–11 km from Slyudyanka; in the third column – 5–11 km from Baikal'sk; in the fourth column – 5 km from the source of the Angara; in the fifth column – 5–11 km from Cape Srednii (the delta of the Selenga); in the sixth column – 5 km from Tankhoi. The seventh column gives the eddy flux intensities for the Southern Baikal region averaged over an area of 900 km^2.

The decay of the Siberian anticyclone late in winter contributes to the passage of the Atlantic cyclones through the Angara valley, which leads to an increase in the velocities of prevailing wind of the northwest direction, maximum in April–May.[7] In the Southern Baikal region the wind weakens. Near the industrial centers of the Angara valley the hydrocarbon concentrations decrease in April compared to December.

An analysis of the results of our numerical experiments has shown that the greatest contribution to the pollution of the atmosphere above Southern Baikal by hydrocarbons comes from the enterprises and vehicles of Slyudyanka and Baikal'sk. The effect of Selenginsk is much less. Emissions of hydrocarbons from the Irkutsk–Cheremkhovo industrial complex, Ulan-Ude, and Gusinoozersk practically do not affect the Baikal region, because of long distances to them, presence of high orographic barriers, and low altitudes of the emission sources. The simulation of the spreading of dust and sulfur and nitrogen compounds emitted by the industrial enterprises of the Angara valley (including emissions from high – up to 350 m – smoke stacks) has shown that for the northwest wind under analogous meteorological conditions the effect of the Irkutsk–Cheremkhovo industrial complex is more pronounced.[4,7,8]

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