Methodological approach to assessing environmental risk (health risk) from air pollution in the Baikal region in a changing climate

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Abstract. The methodological approach to assessing the environmental risk (health risk) from atmospheric pollution in the Baikal region taking into account the changing climate was formulated. It is based on the US EPA’s health risk assessment methodology and impurity concentration estimates by solving the adjoint equation for impurities transport and diffusion. The dynamics of health risk for the population of Irkutsk from atmospheric pollution PM10, PM2.5 due to emissions from possible sources located both in the Baikal region and beyond including sources of transboundary pollution in 1980-2050 under various scenarios of climate change was researched. A tendency for a moderate decrease in the considered risk over the past several decades was shown. In the forecast period until 2050, under both climate scenarios, significant changes in the risk were not noted. The spatio-temporal dynamics of the areas of PM10, PM2.5 sources location that create the increased health risk in relation to Irkutsk was studied. The results indicate the moderate narrowing of the increased risk zone for Irkutsk in the first half of the 21st century. In the period until 2050, the main impact on the population health in the Irkutsk area from emission sources located in the southwest, south and southeast is expected. In case of transboundary pollution, the main danger from sources in Kazakhstan, Mongolia, and China is expected. The results are important to develop proposals for ensuring safety for public health, developing health care and planning environmental protection measures in the Baikal and neighboring regions.

1. Introduction

The Baikal region is a strategically important natural area. At the same time, air pollution here is one of the acute environmental problems [1, 2] and presents a potential hazard to the health of the population [3] and natural ecosystems.

Observed and predicted climate change can change the level of danger of atmospheric pollution. The change in the general circulation of the atmosphere in a changing climate can lead to a significant redistribution of the incoming pollutants and areas that affect the Baikal region in the event of long-range pollution [4]. In this regard, studying environmental risks associated with air pollution is of great interest to the region today. It is especially important to study health risks as one of the most important criteria for assessing the environmental situation.

The goal of this work is to develop a methodological approach to assessing environmentally related health risks (trends in these risks) taking into account climate change. The area of application is...
studying of the dynamics of risk to public health due to atmospheric pollution in regions, in particular, in the Baikal region, in the 21st century. The methodological approach at solving the following tasks is aimed [5]:

1. Assessment of the pollution potential hazard for the region from all possible emission sources located both in the considered area and beyond, including sources of transboundary pollution, under various scenarios of climate change;

2. Determination of sources or areas of sources location that present the greatest potential health hazard to the population of the region under various scenarios of climate change.

2. Materials and research methods
The methodological approach on the methodology for assessing the health risk from environmental pollution by the US Environmental Protection Agency is based [6] and involves an early assessment of carcinogenic and non-carcinogenic risks.

According to [6], the assessment of carcinogenic risk from air pollution is based on using the unit risk factor [6, 7, 8] that characterizes the probability of cancer throughout a person's life due to exposure to a chemical substance with the annual average concentration in the air equal to 1 (mg/m³)⁻¹.

Assessment of non-carcinogenic risk is determined by dividing the annual average concentration in the air by the appropriate reference exposure level (reference concentration, mg/m³). A reference exposure level is used as an indicator of potential noncancer health impacts and is defined as the concentration at which no adverse noncancer health effects are anticipated [6, 8, 9].

Thus, the indicators of the sensitivity of the human body to the pollutants concentration in the atmospheric air are known a priori from the results of biomedical research. The main difficulty in early health risk assessment from air pollution in the Baikal region is the impurity concentration assessment in its ecologically significant territories, which has a number of features.

The first feature is a significant number of potential sources, including transboundary ones, and the presence of various mechanisms of atmospheric pollution in ecologically significant areas of Lake Baikal.

The second feature is uncertainty about the future impact on the atmosphere: changes in the number, location and power of emission sources.

The assessment of the concentration can be obtained in at least two ways. The first is the multiple solution of the impurity transport equation with sources of different intensity and different locations. Another method is more science-intensive, but it requires only a single solution of the adjoint problem [10, 11], by means of which it is possible to assess the degree of potential danger of atmospheric pollution in a given zone from all sources located in the problem solution area under given scenarios of the meteorological regime of the atmosphere. At the same time, no limitations are imposed on the location of the sources and their intensity. This method is used below.

The evolution of impurity $q$ in the atmosphere over the Northern Hemisphere $\Omega$ within $0 \leq z \leq H$ ($H$ – tropopause height) with a velocity characterizing the average transport in the troposphere is considered. For definiteness, we will assume that this is the air velocity on the surface of 500 hPa, which characterizes, first of all, long-range transport. Changes in impurity concentration due to transport in the near region are considered to be due to sedimentation. The generalization to the three-dimensional case is realized trivial.

With sufficient accuracy, long-range transport in the middle troposphere by a two-dimensional equation for impurities transport and diffusion is described [10]. At the same time, background pollution of the atmosphere is neglected as not interesting for solving this problem.

On basis of the Lagrange identity, the foundational problem is corresponded with the adjoint problem [10]. Its solution is the adjoint function $q^*$, which is a weight function that determines the contribution of each pollution source $I$ to the amount of air pollution in an ecologically significant zone (given region) $G$.

The effect of atmospheric pollution from sources in the area $\Omega$ integrated over $G$ region over time $T$ will characterize the functional [10]
Thus, we obtain an expression for solving the first task indicated above in the Introduction.

When solving the second task to determine the areas of sources location that present the greatest hazard to the population in the G region the impurity concentration from a source located in a separate zone \( k \) belonging to the area \( \Omega \) will characterize the functional

\[
Q_k = \int_0^T \int_\Omega I_k q_k^* \, d\Omega_k.
\]

On basis of the pollutant concentrations averaged over a certain period (for a year) the environmental risk research is executed. Therefore, functionals (3), (4) take the form

\[
Q = \frac{1}{T} \int_0^T \int_\Omega I q^* \, d\Omega,
\]

\[
Q_k = \frac{1}{T} \int_0^T \int_\Omega I_k q_k^* \, d\Omega_k.
\]

Taking into account [6, 7, 9], let us set down expressions for calculating the health risk caused by carcinogenic \((i)\) and non-carcinogenic \((j)\) impurities:

- for solving first task

\[
r_i = \frac{R_i}{T} \int_0^T \int_\Omega I_i q_i^* \, d\Omega
\]

(carcinogenic risk),

\[
h_j = \frac{1}{H_j} \frac{1}{T} \int_0^T \int_\Omega I_j q_j^* \, d\Omega
\]

(non-carcinogenic risk),

- for solving second task

\[
r_{ik} = \frac{R_{ik}}{T} \int_0^T \int_\Omega I_{ik} q_{ik}^* \, d\Omega_k
\]

(carcinogenic risk),

\[
h_{jk} = \frac{1}{H_j} \frac{1}{T} \int_0^T \int_\Omega I_{jk} q_{jk}^* \, d\Omega_k
\]

(non-carcinogenic risk).

Here \( R_i \) is the unit risk factor for the substance \( i \), \( H_j \) is reference concentration of the substance \( j \), \( I \) is the source intensity.

Let us also write in a general form of expressions for calculating environmental risks from impurities emitted by sources of the area \( \Omega \):

\[
r_i = \sum_{i=1}^{N} R_i Q_i
\]

(carcinogenic risk),

\[
h_j = \sum_{j=1}^{M} \frac{Q_j}{H_j}
\]

(non-carcinogenic risk).

Accordingly, the expressions for calculating risks from the source of the zone \( k \) of the area \( \Omega \):

\[
r_{ik} = \sum_{i=1}^{N} R_{ik} Q_{ik}
\]

(carcinogenic risk),

\[
h_{jk} = \sum_{j=1}^{M} \frac{Q_{jk}}{H_j}
\]

(non-carcinogenic risk).

In long-term estimates, information on future emissions and sources may not be known. In this case, the methodological approach allows considering a source with a unit emission. We put \( I = \text{const} \).
(for convenience, below we will assume \( I = 1 \)). In this case, expressions (5) - (12) will characterize the unit normalized risks from atmospheric pollution only due to the influence of weather and climatic processes. If the power of the source becomes known (for example, from the region development plan or it will be consider the impact of a specific source on the region), it will be enough (in the linear approximation of the source power influence, which is permissible for long-term planning) multiply the corresponding integrand terms in (3) - (8) or the corresponding summands in (9) - (12) by the actual value of emissions.

To solve the adjoint equation of impurity transport and diffusion and to obtain the fields of adjoint functions, a numerical model is used, which was previously used in other works of the authors including the solution of the adjoint problem in a three-dimensional formulation [5, 12]. Therefore, it will be noted only some features of its construction below.

The region of the solution of the problem is the Northern Hemisphere. The grid area of the numerical model is 90 × 360 knots. The grid spacing of the model is 1°. For the numerical solution of the adjoint turbulent diffusion equation, the splitting method is used [13]. The photochemical processes, coagulation, absorption by droplets of fog and precipitation, radioactive decay include implicitly. Fields of wind and other meteorological quantities are taken from either reanalysis or from the results of scenario calculations of climate change. This provides an opportunity to assess trends of environmental risks in a changing climate.

### 3. Results

On basis of the developed methodological approach, the dynamics of the environmentally related health risk in Irkutsk city due to atmospheric pollution with PM10, PM2.5 particulate matter in 1980-2050 taking into account climate change has been investigated.

The research of the risk to public health from air pollution by microparticles is associated with the increased potential hazard of these substances. They are a mixture with different physical and chemical characteristics depending on their origin and the possibility of their transfer over thousands of kilometers from the source from urbanized and industrial zones, areas of natural fires, oil and gas production, neighboring countries. The health effects of microparticles are varied. In addition to oncological pathology (for example, lung cancer), fine impurities promote to the manifestation of non-cancer diseases of the respiratory and cardiovascular systems, for example, exacerbation of asthma and respiratory symptoms, and an increase in the number of hospitalizations [14].

Within the framework of the study, two tasks were solved.

**Task 1.** Assessment of the dynamics of health risks for the population of Irkutsk from air pollution PM10, PM2.5 due to emissions from possible sources located both in the Baikal region and beyond, including sources of transboundary pollution.

For this, the annual average values of unit normalized non-carcinogenic risks (since information on future sources and emissions is unknown) were calculated in the form of hazard indices for non-carcinogenic diseases for two substances (PM10, PM2.5) from 1980 to 2050 with a step of 5 years. In this case, two series of calculations were performed taking into account two characteristic scenarios of climate change in the 21st century adopted by the Intergovernmental Panel on Climate Change (IPCC) – “moderate” (RCP4.5) and “hard” (RCP8.5) [15]. These scenarios are based on different pathways for greenhouse gas emissions and concentrations in the atmosphere, pollutant emissions and land use in the 21st century that affect the climate system. Thus, the “moderate” scenario assumes a peak in greenhouse gas emissions around 2040, while the “hard” scenario shows a gradual increase in emissions in the period under review.

The following data as meteorological fields were used:

- 1980-1995 – NCEP Climate Forecast System Reanalysis (CFSR) [16];
- 2000-2020 – NCEP FNL Operational Model Global Tropospheric Analyses [17];
- 2025-2050 – data of calculations on the climatic model of the Marchuk Institute of Numerical Mathematics RAS (scenarios RCP4.5 and RCP8.5 [18, 19]).
The figure 1 shows graphs of the dynamics of unit normalized non-carcinogenic risks in 1980-2050 with an interval of 5 years, taking into account various climatic scenarios.

Calculations for Irkutsk show a tendency for a noticeable, but quite moderate decrease in the considered risk (about 15%) over the past several decades have shown. In the forecast period until 2050, under both climate scenarios, significant changes in the hazard to humans from air pollution with particulate matter in the area of Irkutsk were not noted (the trend is several percent).

**Figure 1.** Dynamics of unit normalized non-carcinogenic risk (hazard index of non-carcinogenic diseases) in Irkutsk due to atmospheric pollution with PM10, PM2.5 particles from potential nearby and remote sources in 1980-2020 (left) and in 2025-2050 (on the right).

**Task 2.** Study of the spatio-temporal dynamics of the areas of sources location of atmospheric pollution that create the increased health risk in relation to Irkutsk under various scenarios of climate change.

For this purpose, the annual average values of unit normalized non-carcinogenic risks for Irkutsk from potential sources of PM10, PM2.5 located in different areas relative to Irkutsk (in the k-zones of the Ω region) from 1980 to 2050 with a step of 5 years under various climatic scenarios were calculated. Maps of the dynamics of these risks have been built. However, the presentation in the article of all maps for the period under consideration requires a significant reduction in scale and thus leads to extremely low information content. Therefore, below, as an example, two maps are shown that demonstrate one of the largest and smallest areas of the sources location of increased risk for the Irkutsk city for 1995 and 2010 respectively (figure 2). Areas of different colors show the level of risk created by the source in Irkutsk, when the source is located in this area (area of this color).

According to calculations, taking into account both climatic scenarios, in the first half of the 21st century (after 2005), there is some narrowing of the zone of the location of sources that create increased levels of risk in the Irkutsk region in the first half of the 21st century, in certain directions. In fact, the area of increased risk (for example, the area of the 0.0001 level in figure 2) changes in some directions relative to Irkutsk by tens and even hundreds of kilometers (taking into account the grid spacing on the map of 5 degrees). Thus, the results of solving second task indicate a decrease in the hazard to public health in the Irkutsk area from some remote sources of microparticles in the first half of the 21st century due to the influence of weather and climatic processes.

As in the 1980s and 1990s, in the first half of the 21st century, the main impact on the health of the population of the Baikal region (in the Irkutsk area) from emission sources located in the southwestern, southern and southeastern directions relative to Irkutsk is expected. In case of transboundary pollution, the main danger from sources in Kazakhstan, Mongolia, and China is expected.
It is important to emphasize that the resulting risk assessments are much lower than the acceptable level (unity). This is due to the fact that the unit normalized risk was assessed - the risk due to emissions of 1 g / s intensity produced by only one source, which, however, can be located at any point (zone) of the territory under consideration. The actual value of the risk can be obtained by multiplying the unit normalized risk by the actual value of the source intensity.

Given the uncertainties inherent in long-term assessments, the presented results should be considered as trends in environmental risks for the Baikal region.

Figure 2. An example of dynamics of unit normalized non-carcinogenic risk for Irkutsk from potential sources of PM10, PM2.5 located in different areas relative to Irkutsk in 1995 and 2010 (Irkutsk is shown with a black dot).

4. Conclusion
The methodological approach to assessing the environmental risk (health risk) from atmospheric pollution in the Baikal region, taking into account the changing climate, was formulated.

The dynamics of health risk for the population of Irkutsk from atmospheric pollution PM10, PM2.5 due to emissions from possible sources located both in the Baikal region and beyond including sources of transboundary pollution under various scenarios of climate change was researched. Calculations for Irkutsk a tendency for a noticeable, but quite moderate decrease in the considered risk over the past several decades have shown. In the forecast period until 2050, under both climate scenarios, significant changes in the hazard to humans from air pollution with particulate matter in the area of Irkutsk were not noted.

The spatio-temporal dynamics of the areas of sources location of air pollution that create the increased health risk in relation to Irkutsk under various scenarios of climate change was studied. The results indicate the presence of a certain spatial-temporal dynamics: the moderate narrowing of the zone of increased risk for Irkutsk in the first half of the 21st century due to the influence of weather and climatic processes. An inter-scenario variability of the zone of increased risk until 2050 is insignificant.

In the period until 2050, the main impact on the population health in the Irkutsk area from emission sources located in the southwest, south and southeast is expected. In case of transboundary pollution, the main danger from sources in Kazakhstan, Mongolia, and China is expected.

The results are important to develop proposals for ensuring safety for public health, developing health care and planning environmental protection measures in the Baikal and neighboring regions.

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