On the trends of long-range air pollution in the territories of the Russian Federation in the 21st century

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Abstract. The methodical approach to an assessment of trends of long-range pollution of atmosphere for the ecologically significant zones in view of predicted climatic changes is formulated. Zonal and meridional pollution indices are introduced, which characterize the amount of transported impurities in the latitudinal and meridional directions. The features of the dynamics of long-range atmospheric pollution of the territories of the Russian Federation (RF) under current conditions, in the immediate and distant prospects taking into account the changing climate (from 1980 to 2050) are studied. The results indicate for some strengthening in 2015-2050 compared to the period 1980-2015 the contribution of the west-eastern impurity transport to atmospheric pollution over the northwestern part of the European territory of Russia (ETR), the center of Western and Eastern Siberia, most of the Far East and the Arctic zone of Russia above 70° N and the contribution of the southern impurity transport to atmospheric pollution over the center and southern part of the ETR and the southeastern territories of the Far East. These results are important for the development of proposals for ensuring the environmental safety of Russian regions and for planning economic development of the country's territories that affect the pollution of the environment of ecologically significant zones.

1. Introduction

At present, the priority development of the regions, the ambition for uniformity of the economic space largely becomes the determining factor of the country's development. Management of its spatial development is based on modern mechanisms of strategic planning, which should take into account long-term estimates (forecasts) of environmental safety of regions.

Among environmental problems of the regions, one of the most acute problems remains the problem of air pollution. Its danger consists not only in getting harmful substances into clean air, but also in changing the Earth's climate caused by pollution. Particular dangerous is the pollution of atmospheric air by persistent organic pollutants that are of anthropogenic origin (products of the chemical industry, combustion of fuel, transport, agriculture). Due to low fugacity, high stability and bioaccumulation, these pollutants are transported thousands of kilometers from the source (long-range transport) and accumulate in the tissues of plants and all living organisms, creating a risk to human health \cite{1-3}. 

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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 regions in the event of long-range pollution. In this regard, assessments of the contributions and trends of long-range atmospheric pollution have a high scientific and practical significance in planning the development of the country's regions and ensuring their environmental safety.

The solution of this problem 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, 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. This method is used below.

It should be noted that the objectification and quantitative characteristic of the obtained results are very complicated procedures. In general, the analysis of the dynamics of air pollution in the regions requires the development of certain integral indicators (indices). This will allow to quantitatively characterize the features of the dynamics under study and objectively assess the trends in pollution in the regions.

2. Methodological approach to assessment of long-range atmospheric pollution trends in view of climate change

The transport of the total content of the weightless impurity $q$ (without sedimentation) in the atmosphere over the Northern Hemisphere $\Omega$ with a velocity characterizing the average transport in the troposphere is considered. The generalization to the three-dimensional case is realized trivial.

With sufficient accuracy, long-range transport in the middle atmosphere is described by a two-dimensional equation for the transport and diffusion of an impurity \[4\]. At the same time, background pollution of the atmosphere is neglected as not interesting for solving this problem.

On the basis of the Lagrange identity, the foundational problem is corresponded with the adjoint problem \[4\]. 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) $G$. By the values of $q^*$, it is possible to regionalize the whole territory of the country, marking dangerous zones in relation to the pollution of the atmosphere in the $G$ region.

The effect of atmospheric pollution integrated over $G$ over time $T$ will characterize the functional \[4\]

$$ Q = \int_{0}^{T} \int_{\Omega} Iq^* \, d\Omega. \quad (1) $$

We set $I = \text{const}$ (for convenience of writing we will assume below that $I = 1$), then the functional (1) will characterize the pollution of the atmosphere only due to the effect of weather and climate processes, which is required to achieve the goal of the work. In this case, expression (1) takes the form

$$ Q = \int_{0}^{T} \int_{\Omega} q^* \, d\Omega = \int_{0}^{T} \int_{\psi_N}^{\psi_S} \int_{\lambda_W}^{\lambda_E} q^* \, d\lambda \, d\psi, \quad (2) $$

where $\lambda_W$, $\lambda_E$, $\psi_S$, $\psi_N$ — respectively, the western and eastern longitudes, the southern and northern latitudes of the region boundaries $\Omega$. Information on the field of wind speed and other meteorological quantities is given on the basis of actual measurements or based on the results of numerical modeling, including taking into account climate change. Then, an analysis of the time variations of the $Q$ field makes it possible to assess the trends of long-range atmospheric pollution of a given region in a changing climate. However, a direct analysis of the $Q$ field is inconvenient.

Therefore, it is advisable to introduce indices characterizing the amount of transported impurities in the latitudinal or meridional directions for the objectivization and quantitative characterization of atmospheric pollution dynamics. As an analogue it is convenient to use the approach of A.L. Katz to the introduction of atmospheric circulation indices \[5\].
We denote the coordinates of the center of the domain $G$ by $(\lambda_0, \psi_0)$ with $\lambda_W \leq \lambda_0 \leq \lambda_E$, $\psi_S \leq \psi_0 \leq \psi_N$ and consider the integrals (indices)

$$
\begin{align*}
M_Z &= \frac{1}{Q} \int_0^\tau \int_{\psi_S}^{\psi_W} \int_{\lambda_W}^{\lambda_E} q^* d\lambda d\psi \left( \int_{\lambda_W}^{\lambda_E} q^* d\lambda - \int_{\psi_S}^{\psi_W} q^* d\psi \right), \\
M_M &= \frac{1}{Q} \int_0^\tau \int_{\psi_S}^{\psi_W} \int_{\lambda_W}^{\lambda_E} q^* d\psi d\lambda \left( \int_{\psi_S}^{\psi_W} q^* d\psi - \int_{\lambda_W}^{\lambda_E} q^* d\lambda \right). 
\end{align*}
$$

The dimensionless index $M_Z (-1 \leq M_Z \leq 1)$, which is advisably called the zonal pollution index, shows how the west-east (at $M_Z > 0$) or east-west (at $M_Z < 0$) impurity transport affects the pollution of the ecologically significant zone $G$. Similarly, the index $M_M (-1 \leq M_M \leq 1)$ shows how southern (at $M_M > 0$) or northern (at $M_M < 0$) impurity transport affects the pollution of zone $G$. This index respectively should be called the meridional pollution index. The high value of the $M_Z$ index does not necessarily correspond to the small index $M_M$. In certain periods and seasons, there is a strengthening or weakening of both indices simultaneously.

Finally, it is convenient to use one more (generalized) index quantitatively characterizing the direction from which the pollution of the $G$ region is.

$$
M = \arccos \frac{M_Z}{\sqrt{M_Z^2 + M_M^2}}.
$$

Thus, the content of the methodical approach to the assessment of long-range atmospheric pollution trends is as follows:

- to get the fields of the adjoint function $q^*$ for given moments of time and a given zone $G$ by solving the adjoint problem with the actual or prognostic (in view of climate changes) meteorological fields;
- to execute calculations using the expression (2);
- to execute calculations using expressions (3) and analyze the obtained values of the indices $M_Z$ and $M_M$. Their dynamics will fully characterize the trends of long-range atmospheric pollution over the area $Q$ with choosing $G$ as an ecologically significant zone. These results will allow us to reasonably view the level of ecological security in region $G$ and, if necessary, carry out measures to protect the atmosphere. For visualization, it is convenient to use the generalized index (4).

A methodical approach in detail is set out in [6-7].

3. A numerical model that realizes the solution of the adjoint problem

The description of some variants of the numerical model realizing the solution of the adjoint problem in a three-dimensional formulation is given in the works [2,8]. Therefore, only some features of its construction will be noted below.

The region of the solution of the problem is the Northern Hemisphere. The grid area of the numerical model is $90 \times 360$ knots. The grid spacing of the model is $1^\circ$. For the numerical solution of the adjoint turbulent diffusion equation, the splitting method is used [4].

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 in long-range atmospheric pollution in a changing climate.

4. Results

Currently, according to the administrative division in Russia, there are 12 economic regions that completely or partially coincide with the borders of federal districts. Since some areas (West Siberian, East Siberian, Far Eastern) have a large spatial extent, primarily from the north to the south, and in these areas there is a significant differentiation of economic activities due to climatic and geographical conditions; these areas at realization of the calculations are divided into several parts.
In particular, the northern parts of these regions above the 70th latitude, which are part of the Arctic zone of the Russian Federation, are separately identified. This included the territory west of the Taimyr Peninsula, the Taimyr Peninsula and the zone to the east of the Taimyr Peninsula.

In the West-Siberian and East-Siberian regions, zones between the 60th and 70th latitudes and the remaining areas south of the 60th latitude are also identified, since the zones of economic activity are approximately divided along it.

The Far Eastern economic region is also divided into 3 zones: Western (Sakha Republic (Yakutia), Eastern (Chukotka Autonomous District, Magadan region, Kamchatka Territory) and South-Eastern (Amur Region, Khabarovsky Territory, Primorsky Territory, Sakhalin Region).

As a result of this division, 19 ecologically significant zones were identified, for which the dynamics of long-range atmospheric pollution were evaluated. The $Q$ fields were calculated from 1980 to 2050 with a step of 5 years for each of these zones. The following data were used as meteorological fields:

- 1980-1995 – NCEP Climate Forecast System Reanalysis (CFSR) [9];
- 2000-2015 – NCEP FNL Operational Model Global Tropospheric Analyses [10];
- 2020-2050 – data of calculations on the climatic model of the Marchuk Institute of Numerical Mathematics RAS (RCP8.5 – the "hardest" scenario [11]).

Visualization of the $Q$ fields was not carried out due to the large number of investigated zones.

Seasonal (January, April, July, October) and yearly indices $M$ and $M_z$ as well as indices $M$ were calculated for the identified zones.

The figure 1 shows maps of the distribution of the yearly index $M$ on the territory of Russia in 1980-2050 with an interval of 5 years.

The minimal dynamics of the $M$ index is marked in the Kaliningrad region and in the southern part of the West Siberian region below the 60th latitude and points respectively to a stable western and west-southwestern transport. Here the variations do not exceed 10°.

Small changes in the index $M$ (from 10° to 30°) can be traced:

- in the North-West region – between W and W-SW directions;
- in the Northern region as well as in the central part of the West Siberian and East Siberian regions (between 60th and 70th latitudes) – between W-SW and S-SW directions;
- in the northern (above the 70th latitude) and in the western part of the Far East region – between SW and S directions.

The expressed dynamics of the $M$ index (from 60° to 95°) is developed:

- in the Central Chernozem region – between the W-SW and S-SE directions;
- in the Volga, North-Caucasian regions and the eastern part of the Far Eastern region – between the W and S directions.

Strong changes in the direction of impurity transport (up to 135°) from the western to the southeast are marked in the southeastern part of the Far Eastern region. Obviously, this is a consequence of the strengthening of the Far Eastern monsoon.

In general, the analysis of changes in the $M$ index for 70 years indicates its very complicated dynamics. Significant variations in directions, from which the pollution of the ecologically significant zones come, are observed in certain years for some territories, and it is difficult to identify patterns here. But for a number of regions, we can note some trends in the direction of pollutants.

For example, it can be seen that the pollution in the North-West region occurred from 1980 to 2010 from W and W-SW directions, and from 2015 to 2050 – from the western direction. This indicates to the intensification of the West-Eastern transport of the impurity to the pollution of the atmosphere in the given territory. The trend of strengthening the west-east transport can also be noted from 2020-2025 for the central part of the West Siberian and East Siberian regions, the northern, western and eastern parts of the Far Eastern region as well as for the territories of the East Siberian and Far Eastern regions above the 70th latitude.
Figure 1. Dynamics of the distribution of the $M$ index on the territory of the Russian in 1980-2050.
In the Central Chernozem region, Volga region and the southeastern part of the Far Eastern Region, on the contrary, approximately from 2015 there is a tendency to change the direction of transport from the zonal (W and W-SW) to the meridional (S-SW and S-SE). In general, the sources that are located to the south of these regions will be the most dangerous for long-range atmospheric pollution in the near decades.

Practical application of the obtained results seems to be important, first of all, on planning the development of industries in the regions that may influence the long-range pollution of other Russian territories.

For example, the spatial development of Russia can be successfully implemented only on the basis of the accelerated development of transport systems. At present, the transport industry has become one of the most dynamically developing industries in Russia. At the same time, transport is the leading source of air pollution.

According to the Ministry of Transport of Russia, reconstruction and construction of new highways and railway lines implement in the center, in the south, north and northwest of the European territory of Russia (ETR), in the Urals, Siberia and the south-southeast of the Far East. The infrastructure of air and water transport is actively developing.

In the near decades, it is planned to intensify the development of transport in the center of Siberia, the western part of the Far East and in the Arctic regions (Murmansk region, the Northern Urals, etc.) according to the necessity for deep integrated development of these territories [12]. When planning transport and industrial facilities in these territories, it is necessary to take into account the possible strengthening in the contribution to the long-range pollution of the regions located east of these territories what with the noted tendency of intensification of the West-Eastern transport in Siberia and the Far East including the eastern part of the Russian Arctic.

The transport development strategy envisages the construction of large transport hubs in the south of Russia and the increase in the capacity of the ports of Novorossiysk, Taman, Rostov-on-Don. Intensive development of transport infrastructure will give a powerful impetus to the development of industrial zones in these territories. Considering the possible strengthening in the southern transport of pollutants in the Central Chernozem region and Volga region, some care is required to ensure the environmental safety of atmospheric air when planning the development of the southern regions of the country.

5. Conclusion

The methodical approach to an assessment of trends of long-range pollution of atmosphere for the given ecologically significant zones in view of predicted climatic changes is formulated.

Calculations of the introduced zonal and meridional pollution indices characterizing the amount of transported impurities in the latitudinal and meridional directions for January, April, July, October and year for the period 1980-2050 are performed.

In general, the results indicate quite definite trends in long-range air pollution – for some strengthening in 2015-2050 compared to the period 1980-2015

- the contribution of the west-eastern impurity transport to atmospheric pollution over the northwestern part of the ETR, the center of Western and Eastern Siberia, most of the Far East and the Arctic zone of Russia above 70º N;
- the contribution of the southern impurity transport to atmospheric pollution over the center and southern part of the ETR and the southeastern territories of the Far East.

These results are important for the development of proposals for ensuring the environmental safety of Russian regions and for planning economic development of the country's territories that affect the pollution of the atmosphere of ecologically significant zones. In particular, some care is required when planning the location of new transport and industrial facilities that release polluting into the atmosphere. In addition, the relevance of the control of transboundary air pollution from the nearest northern countries of Europe, Middle and South-East Asia is increasing.
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