Ensuring the Environmental Safety of Large Cities Based on an Innovative Approach to Predicting Atmospheric Air Pollution

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Abstract. Sustainable development of territories should be based on ensuring sufficient quality of the air basin. Air quality management, in turn, is based on adequate predictive models that allow the development of a number of measures to improve its quality. In this regard, the article is devoted to the discussion of issues of ensuring the environmental safety of territories, including rural ones, on the basis of the innovative approach developed by the authors to the implementation of the forecast of the air quality of the lower layer of the atmosphere. The choice of the object of study – the city of St. Petersburg – is connected with the fact that the city has a network of posts for environmental monitoring of the state of the air environment, providing up-to-date information for making a forecast scheme. As a result of the conducted research, the authors identified groups of meteorological and synoptic characteristics, as well as formed databases of hydrometeorological data and series of concentrations of a number of impurities for the period from 2006 to 2014. It is assumed that the successful application of the developed scheme for predicting the quality of atmospheric air will ensure the environmental safety of the population of urban and rural areas.

1. Introduction

Ensuring the ecological safety of the territories within which localities are located is one of the most important tasks of modern geoecology as an applied science [1]. At the same time, the quality management of the air basin of the lower layers of the atmosphere is one of the priority principles for ensuring environmental safety. In turn, air basin quality management cannot be carried out without up-to-date information on current and future levels of surface air pollution, which is impossible without a high-quality predictive scheme.

The obvious achievements of modern science in the development of a number of mathematical models that make it possible to predict the quality of the air basin within populated areas have left a significant number of very important issues without solution and attention [2]. Among them, as it seems
to the authors, it is still relevant to identify and clarify the contribution of synoptic conditions to the formation of air pollution levels within the study area, as well as geographical parameters, including surface height.

As is known, in the XX century there were already various predictive models containing a number of predictors [3, 4, 5], including: the direction and speed of transport within the lower air layer; atmospheric stratification and the degree of vertical mixing of the lower air layers; the temperature state of the lower air layers; the presence of inversions, fogs and precipitation; numerical characteristics of the synoptic situation, and others. It should be noted that the main forecasting methods that allow us to evaluate the quality of atmospheric air in accordance with the obtained quantitative values of the integral parameter P were numerical calculations of sequential graphical regression and linear regression analysis. However, in the twenty-first century, the above-mentioned quantitative approaches and methods of linear regression are outdated and cannot give adequate results for a number of reasons, the main of which are the significant fluctuations in the climate system over the last 30 years, since the 1990s.

In particular, as many researchers point out, due to the implementation of various scenarios of the climate system, it is necessary to fundamentally revise the known models and develop, followed by the introduction of innovative approaches and technologies to solve the problem of adequate modeling of the occurrence of conditions for the formation of various levels of surface air pollution within the studied territories, taking into account synoptic and weather-climate variability, as well as geographical localization.

Very interesting in this regard is the use of expert methods that allow not only to take into account a significant number of predictors, but also to apply the possibilities of probabilistic methods for predicting stochastic processes in the lower layer of the atmosphere.

It should be noted that the introduction of mathematical forecasting methods in the field of applied meteorology has been going on for more than 60 years, during which a significant number of theoretical and practical problems have been very successfully solved [5, 6]. In particular, the specialists of the Main Geophysical Observatory named after A. I. Voeikov in the XX century developed effective principles for predicting the quality of atmospheric air, based on the synoptic-statistical method and the method of constructing mathematical models. At the same time, based on the normative document RD 52.04.306 – 92, which set out the theoretical principles of forecasting atmospheric air pollution, the numerical values of the integral parameter P were estimated, which were determined by a group of meteorological characteristics.

It is important to understand that these principles for making forecasts of atmospheric air quality were developed in the middle of the XX century and allowed us to cope with this task very convincingly, demonstrating for more than 40 years a good convergence between the real and predicted values of the predictor parameter P. However, it seems to the authors that the above principles in the XXI century can not give results that satisfy the actual situation for a number of reasons, among which the most important role is played by static mathematical dependencies that do not take into account the dynamics and multivariance of the simulated situation.

In this regard, probabilistic modeling methods are very interesting, among which, according to the authors, the “decision tree” method deserves special attention, which allows us to take into account both the variability of synoptic situations and their contribution to the formation of air pollution levels, and heterogeneous meteorological characteristics that take part in the accumulation or dispersion of impurities in the lower layer of the atmosphere.

So, in 2016, the authors attempted to test the “decision tree” method for predicting air quality within St. Petersburg. It should be noted that the “decision tree” method for the implementation of the task of predicting the level of air pollution in the lower atmosphere has not been previously used, in this regard, it can be considered innovative [7, 8, 9]. The choice of the object of testing of the above method was associated with the diversity of synoptic situations in the vicinity of St. Petersburg, which is explained by the proximity of the Baltic Sea and the Atlantic Ocean, as well as the presence of the polar front, the influence of which, due to geographical localization, is most active in the autumn – winter period of the
year. It is also important to note that the abundance of cyclonic formations generated within the polar front; the predominance of western latitudinal transport, which contributes to the removal of warm and fairly clean (dust-free) air from the Atlantic, forms the specific features of the marine climate of St. Petersburg, which generally contribute to the dispersion of impurities in the surface air layer. Some instability of the weather and climate regime within St. Petersburg, observed by the authors from 2006 to 2014, made significant adjustments to the repeatability and specifics of the synoptic conditions of the studied territory, which significantly affected the nature of the dispersion of impurities. I would also like to note that this instability of the weather and climate regime can be explained by the implementation of one of the scenarios for the development of the planetary climate system and is not related to anthropogenic activity [10, 11, 12].

The prognostic schemes developed by the authors for the implementation of the “decision tree” method in relation to the surface air quality within St. Petersburg for the cold and warm seasons showed a very close convergence with the actual component-by-component concentrations of the main impurities of the lower air layer (the convergence was about 87 % on average) [13,14]. However, it seems to the authors that a very important, but also quite variable part of the method is its synoptic component, which is a complex of synoptic situations that have a high repeatability over a certain period of time. In this regard, within the framework of this article, it makes sense to consider in detail the features of synoptic processes in the north-west of Russia in recent years (from 2006 to the present) and their contribution to the formation of the quality of the air basin of the region.

2. Results and discussion
As previously conducted studies of the authors have shown, both permanent centers of atmospheric action, including the Azores, Arctic and Greenland maxima, as well as the Icelandic minimum, and seasonal ones—the South Asian minimum and the Asian maximum—have a significant impact on the territory of the north-west of Russia. In addition, a very important role in the formation of circulation conditions is played by the polar front, which is located in the immediate vicinity of the studied region, on the surface of which a series of cyclones are very actively formed.

Cyclones moving from the west (during the year), north-west (mainly in the autumn-winter period) and south-west (in spring and summer) generally contribute to the dispersion of surface impurities. However, with a decrease in the speed of movement or short-term stationing of the cyclone in its warm sector against the background of low (layered) clouds and fogs due to the advection of warm air, the accumulation of pollutants in the lower air layers was observed (figure 1).

Anticyclones enter the study area, mainly from the north (spurs of the Arctic Maximum) (figure 2), northwest (spurs of the Greenland maximum) or west (spurs of the Azores maximum), although ultrapolar (eastern) intrusions during the cold period of the year are not excluded against the background of the activation of the seasonal Asian maximum pressure.

Due to the low speed of movement and the usual stationing of anticyclones within the territory of the north-west, low-cloud, dry weather is established with frequent inversions and, as a result, with an intensive accumulation of a number of anthropogenic impurities in the surface layer. Elevated inversions, as well as surface inversions, are observed in anticyclonic weather, keeping impurities in the boundary layer, contribute to the accumulation of impurities, providing high levels of pollution of the air basin. According to the authors’ research, within St. Petersburg, the maximum number of days per year (up to 20 days per month) with inversions was observed in 2006–2014 in spring (May) and summer (July), significantly (less than 5 days per month) decreasing in autumn (November) and winter (December).
Figure 1. The warm sector of the cyclone with a pressure in the center of 980 hPa in the area of St. Petersburg. Synoptic map April 10, 2021, 00 UTC (Archiv der 00 UTC USNO-Bracknell-Bodenanalyse (ab 27.01.1998) [15].

Figure 2. Stationing of the spurs of the Arctic anticyclone with a pressure of 1031 hPa in the area of St. Petersburg. Synoptic map March 10, 2021, 00 UTC (Archiv der 00 UTC USNO-Bracknell-Bodenanalyse (ab 27.01.1998) [15].

The accumulation of surface impurities is also observed during the establishment of a low-gradient baric field, when due to insignificant horizontal gradients of surface pressure, a decrease in wind speeds is observed and, as a result, an intensive accumulation of anthropogenic impurities occurs, causing a high level of atmospheric air pollution within the study region (figure 3).
Figure 3. Low-gradient baric field of high pressure in the area of St. Petersburg. Synoptic map April 19, 2021, 00 UTC (Archive 00 UTC USNO-Bracknell-Bodenanalysen (ab 27.01.1998) [15].

The studied series of synoptic surface maps compiled over Europe for 00 UTC according to Archiv der 00 UTC UKMO-Bracknell-Bodenanalysen (ab 27.01.1998) [15] showed that in 2006–2021 the frequency of anticyclone stationing, as well as cases of a low – gradient baric field, slightly increased, which confirms the opinion of a number of researchers about some instability of the weather and climate regime in the north-west of Russia and, in general, increases the number of days dispersion of anthropogenic impurities in the lower layer of air.

Thus, the scheme implemented by the authors for predicting the quality of the lower air layer using the “decision tree” method is based on information about the synoptic process that determines a particular level of air pollution. Verification of this scheme on the example of the conditions of St. Petersburg showed a very convincing convergence between the calculated and actual values: more than 90% for the cold and up to 87% for the warm seasons of the year.

Some instability of the synoptic processes of the period 2006–2021 revealed by the authors requires more attention and consideration in the further development of innovative methods for forecasting the quality of the air basin of territories.

3. Conclusion
In conclusion, the main results and conclusions obtained in the course of the study are formulated:

− archives of the initial data of standard meteorological, atmospheric radiosonding data, synoptic positions and the level of atmospheric air pollution for the period from 2006 to 2014 are formed, which are necessary to determine the expected level of atmospheric air pollution in St. Petersburg;
− the characteristic groups of synoptic processes in St. Petersburg for the period from 2006 to 2014 were clarified;
− schemes have been developed using the “decision tree” method, which allows us to determine the expected level of atmospheric air pollution for the warm and cold periods of the year, day and night hours, with a lead time of 12 hours, with a justifiability of 84–91%.

Thus, the successful implementation of the goal of this study indicated, in the first approximation, the possibility of using the “decision tree” method to develop a scheme for predicting the level of atmospheric air pollution on the example of large cities and urbanized zones, as well as the prospects for its further use.
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