ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (Ph.D.) on educational program 8D050204 - "Meteorology"

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on the topic: "Effect of meteorological parameters on air quality in large cities of Kazakhstan"

General description of work. The dissertation is aimed at analyzing the influence of meteorological conditions on $PM_{2.5}$ concentrations in atmospheric air.

Relevance of the work.

Atmospheric air pollution with fine $PM_{2.5}$ particles (2.5 micrometers in diameter or less) is a serious problem that attracts the attention of scientific communities worldwide. The growing interest in $PM_{2.5}$ is due to its harmful effects on human health. $PM_{2.5}$ is one of the leading factors of global mortality and is associated with diseases of the respiratory and cardiovascular systems, and also has a significant impact on the climate, affecting the formation of clouds and radiation balance in the atmosphere.

Currently, the cities of Central Asia are among the most problematic in terms of air pollution in the world. According to the 2021 IQAir ranking, Tajikistan, Kyrgyzstan, Uzbekistan, Kazakhstan and Turkmenistan ranked 4th, 7th, 12th, 23rd and 44th in the world in terms of $PM_{2.5}$ exposure, respectively. However, the $PM_{2.5}$ pollution levels in major cities of Central Asia do not correspond to their population size compared to world capitals. For example, the ratio of $PM_{2.5}$ concentrations per million population in Central Asian cities ranged from 16.85 (in Almaty) to 66.85 (Dushanbe), while in other capitals it ranged from 0.95 to 3.75. This highlights the need for comprehensive research to identify the causes and factors affecting air quality in these cities.

Seasonal and spatial variations of pollutants, along with their primary sources, are crucial data needed to implement effective measures and establish the necessary regulatory framework and legislation to reduce the pollution levels and protect public health. For a comprehensive assessment of $PM_{2.5}$ air pollution, a primary step involves quantitatively assessing its main contributing factors. Anthropogenic emissions are widely considered as the primary factor influencing $PM_{2.5}$ concentrations. However, under stable emission conditions, meteorological conditions play a key role in shaping pollution episodes, as they can determine how efficiently air masses disperse pollutants or, conversely, accumulate them in specific areas.

Foreign studies indicate that numerous meteorological factors, including air temperature, wind speed, humidity, precipitation, solar radiation, atmospheric pressure, and the height of the atmospheric boundary layer, are closely linked to $PM_{2.5}$ concentrations. In addition to local emissions and the impact of meteorological factors, regional transport of air pollutants is also possible. In Kazakhstan, despite the seriousness of air quality issues, research on the impact of meteorological parameters on pollutant concentrations remains limited or has not been conducted. Therefore, investigating the relationships between meteorological parameters and $PM_{2.5}$ concentrations in major cities of Kazakhstan is a relevant scientific direction, as the findings from such studies can serve as a basis for predicting pollution levels and developing sustainable air quality management strategies.

The aim of the study – analysis of temporal variations in $PM_{2.5}$ concentrations in large cities of Kazakhstan and investigate the impact of meteorological parameters on $PM_{2.5}$ concentrations. The following tasks were set accordingly:

1. Investigate the temporal variations (annual, seasonal, monthly, daily, and hourly) of $PM_{2.5}$ concentrations in large cities of Kazakhstan (Almaty, Astana) and compare them with other cities of Central Asia (Ashgabat, Bishkek, Dushanbe, Tashkent).
2. Identify the main sources of $PM_{2.5}$ in the air in large cities of Kazakhstan.
3. Analyze the influence of meteorological parameters such as air temperature, precipitation, wind speed, relative humidity, and the height of the atmospheric boundary layer on the concentration level of $PM_{2.5}$.
4. Evaluate the characteristic trajectories of air masses during episodes with high concentrations of $PM_{2.5}$ in the cities of Almaty and Astana.
5. Assess the impact of quarantine measures related to the COVID-19 pandemic on the change in air quality in Central Asian cities.

The objects of the study: concentrations of $PM_{2.5}$ in atmospheric air in large cities of Kazakhstan.

The subject of the study: the influence of meteorological parameters on changes in $PM_{2.5}$ concentrations in the atmospheric air of large cities of Kazakhstan.

Sources of research materials

Archival materials, including data on pollutants ($PM_{2.5}$, TSP, NO_2, SO_2, CO) obtained by monitoring stations of the RSE Kazhydromet and the US Embassy; meteorological and sounding data from meteorological and aerological stations of the RSE "Kazhydromet"; information on the height of the atmospheric boundary layer according to the ERA5 reanalysis data; country-specific pollutant emissions data (SO_2, NO_x and CO) obtained from the global emissions inventory of the Emissions Database for Global Atmospheric Research (EDGAR); air mass trajectories calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model.

Research Methods

During the dissertation work, an analysis of temporal variations in $PM_{2.5}$ was conducted in the cities of Almaty, Astana, Ashgabat, Bishkek, Dushanbe, and Tashkent. The influence of meteorological parameters on $PM_{2.5}$ concentrations was assessed using correlation analyses: Convergent Cross Mapping (CCM) and linear Pearson correlation. The corresponding calculations were performed using the causal-ccm (v. 0.3.3) and scipy (v. 1.8.1) libraries in Python 3.10. Two common methods were employed to calculate the atmospheric boundary layer height: the Richardson number (Ri) and the potential temperature (PT) gradient method, for which wind, temperature, and humidity profile data were required. To investigate possible regional transport of air pollutants, a 72-hour backward trajectory analysis was conducted using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by the National Oceanic and Atmospheric Administration (NOAA). Analysis of ratios (SO_2/NO_x and CO/NO_x) using EDGAR emission data was employed to identify pollution sources (stationary or mobile) in the studied cities**.**

The main research results

1. Major cities in Central Asia are subject to severe air pollution, characterized by annual concentrations of $PM_{2.5}$ particles exceeding World Health Organization (WHO) standards by 4.3-12.6 times.

2. The high level of $PM_{2.5}$ air particle pollution in Almaty and Astana cities is influenced by a seasonal pattern coinciding with intensive coal burning. Additionally, meteorological parameters can impact the dispersion limitation of pollutants.

3. Official inventory studies traditionally identify transportation as a major source of air pollution. However, research results on the impact of the COVID-19 lockdown on air quality show that this sector was not the only major factor influencing pollution levels.

4. Meteorological parameters significantly influenced $PM_{2.5}$ concentrations, especially during winter and autumn periods in all studied cities. Negative correlations were observed between $PM_{2.5}$ concentrations and air temperature, wind speed, and precipitation, while positive correlation was found with relative humidity.

5. Cluster analysis results indicate that most episodes with high $PM_{2.5}$ concentration in Almaty occurred during slowly moving air masses, while in Astana, pollutants could be transported from neighboring industrial cities like Karaganda and Pavlodar.

6. Research findings revealed a clear negative correlation between the daily average $PM_{2.5}$ concentration and the height of the atmospheric boundary layer (PBLH) at 12:00 UTC. Thus, high $PM_{2.5}$ concentrations in winter months (94.0 μg/m³) corresponded to lower PBLH (392.5 m), while low PM2.5 concentrations in summer months (9.9 μg/m³) were associated with higher PBLH values (1969.4 m). During the cold half of the year, the highest 20% of $PM_{2.5}$ concentrations were observed with lower PBLH values (less than 500 m above ground level) and calm wind conditions.

The scientific novelty of the research

The novelty of the obtained results lies in the comprehensive assessment of the impact of meteorological parameters on temporal changes in $PM_{2.5}$ concentrations and $PM_{2.5}$ concentrations using modern statistical methods. Within this study, an analysis of the atmospheric boundary layer height and wind characteristics on pollution levels was conducted for the first time, and episodes with high $PM_{2.5}$ concentrations were examined. The research included an analysis of the impact of quarantine measures adopted during the COVID-19 pandemic on $PM_{2.5}$ levels in major cities of Kazakhstan and Central Asia. The results indicate that the reduction in air pollutant concentrations during the lockdown was insignificant, and in some cities, an increase was observed. Furthermore, the incorporation of practical recommendations to improve air quality in Kazakhstan's cities, based on the analysis results, adds practical novelty and relevance to the study in the context of air quality management.

Scientific and practical significance of research work

The scientific and practical significance of this work lies in obtaining new scientific knowledge and data that contribute to a deeper understanding of the mechanisms of atmospheric air pollution by fine particles $PM_{2.5}$ and identifying the features of the contribution of meteorological parameters to the conditions for the formation of episodes with high values of $PM_{2.5}$. The recommendations obtained as a

result of research can be used in the development of effective management strategies and air quality control to ensure public health and sustainable development of cities and regions. Additionally, the study serves as a foundation for further research in the fields of meteorology and air quality, including the use of mathematical models to develop theoretical concepts and forecasting.

The validity and reliability of the results are confirmed using several statistical methods, such as correlation analysis and cluster analysis. A detailed description of the utilized data and methods allows for the replication of the research results.

Relation of the thesis with research and government programs

The work was carried out within the framework of financing the projects of the Ministry of Science and Higher Education of the Republic of Kazakhstan: "Comprehensive assessment of air pollution in Almaty: source-identification, spatiotemporal assessment" for 2021-2023 (AP09260359) and "Development of a research program to improve air quality in Nur Sultan and Almaty using state-of-the-art analytical methods and modeling tools" for 2021-2023 (BR10965258).

Key provisions presented for defense:

1. $PM_{2.5}$ levels in Central Asian cities exceed the WHO annual limit by 4.3–12.6 times. The studied cities use an outdated method of compiling an inventory of pollutant emissions.

2. The lockdown of COVID-19 did not have a significant effect on the levels of $PM_{2.5}$ concentrations in the studied cities.

3. Slow-moving air masses are typical for episodes with high concentrations of $PM_{2.5}$ in Almaty (67%), while the air in Astana may be exposed to neighboring industrial cities.

4. Average daily concentrations of $PM_{2.5}$ have a negative correlation with the height of the atmospheric boundary layer (PBLH), wind speed in the boundary layer and ventilation coefficient.

Approbation of practical results of the work

The main results of the work were presented at the following international conferences, seminars and forums: the International Conference "Farabi Alemi" (Almaty, 2021); the Asian Aerosol Conference (Taipei, Taiwan, 2022), the second Central Asian Air Quality Conference (Astana, 2023), the 5th International Congress Environmental Chemistry (Antalya, Turkey, 2023).

Publications

The results of the work performed are reflected in 4 scientific papers, including Atmospheric Environment (Q1 according to WoS, Impact factor 5.0, Percentile 93%), Urban Climate (Q1 according to WoS, Impact factor 6.4, Percentile 95%), Aerosol and Air Quality Research (Q2 according to WoS, Impact factor 4.0, Percentile 77%), Environmental Processes (Q3 according to WoS, Impact factor 4.4, Percentile 75%).

The personal contribution of the Ph.D. candidate to the preparation of each article was as follows:

In the articles "Cities of Central Asia: New hotspots of air pollution in the world" (Atmospheric Environment, 309, 119901, Q1 WoS) and "Planetary Boundary Layer and its Relationship with PM2.5 Concentrations in Almaty, Kazakhstan"

(Aerosol and Air Quality Research, 22(8), 210294, Q2 WoS), Madina Tursumbayeva is the first author. The doctoral candidate conducted a literature review on the research topic, participated in the qualitative and quantitative assessment of spatiotemporal changes in pollutant concentrations and meteorological parameters, prepared initial drafts of the articles covering the introduction, methodology, results, conclusions, and graphical representation. Additionally, she participated in the editing process of the final versions of the articles. Furthermore, Madina Tursumbayeva contributed to formatting the articles according to the journal's requirements and improving the articles at each stage of the review process.

In the article "An episode-based assessment for the adverse effects of air mass trajectories on PM2.5 levels in Astana and Almaty" (Urban Climate – 2022, 49, Q1 WoS), Madina Tursumbayeva is an author. She participated in the qualitative and quantitative assessment of spatiotemporal changes in meteorological parameters and $PM_{2.5,}$ wrote initial drafts, and contributed to the improvement and refinement of the article. Additionally, Madina O. Tursumbayeva was involved in formatting the article according to the journal's requirements and enhancing the article after each stage of the review process.