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Mykhailo SAVENETS[1], PhD (Geogr.), senior researcher
ORCID ID: 0000-0001-9429-6209
e-mail: savenets@uhmi.org.ua

Sofiia KRAINYK[1], engineer
ORCID ID: 0009-0004-6299-0983
e-mail: sofiakrajnik7@gmail.com

Daria HRAMA[2], student
e-mail: aeweriss@gmail.com

Maryna RUDAS[2], student
e-mail: rudas22ed@gmail.com

Oksana SKLIAR[2], student
e-mail: oksanasklar16@gmail.com

[1]Ukrainian Hydrometeorological Institute of SESU and NASU, Kyiv, Ukraine
[2]Taras Shevchenko National University of Kyiv, Ukraine

STATISTICAL ASSESSMENT OF THE NET CONTRIBUTION OF CLIMATE CHANGE TO THE FORMATION OF POLLUTANT CONCENTRATIONS IN THE ATMOSPHERIC AIR OVER THE TERRITORY OF UKRAINE

Background. ***Air pollution and climate change are among the key factors of negative anthropogenic impact on the environment. The variability of pollutants largely depends on emissions; however, the role of climate change in shaping pollutant concentrations remains insufficiently studied. This aspect is crucial for long-term planning to improve air quality and develop emission reduction strategies. This study presents an analysis of the net contribution of climate change to the formation of harmful pollutant concentrations using a statistical approach to time series decomposition.***

Methods. ***The research is based on monthly emission and concentration data of nitrogen dioxide (NO_2), formaldehyde (CH_2O), and tropospheric (ground-level) ozone (O_3) from the Copernicus Atmospheric Monitoring Service (CAMS) reanalysis for the period from 2003 to 2021, as well as air temperature, wind speed, and precipitation data from the ERA5 reanalysis. The application of an additive statistical model allowed the decomposition of pollutant concentrations' time series into seasonal (intra-annual) components, interannual trends, and interannual dependencies of NO_2, CH_2O, and O_3 variability on fluctuations of climate parameters.***

Results. ***Seasonal variability in pollutants' concentrations, which depends both on meteorological changes and differences in pollutant emissions, explains 61–74 % of the total variability of NO_2 and about 90 % of CH_2O and O_3. The interannual trends of the studied pollutants, which are influenced by changes in anthropogenic load, ranged from 0.6 % to 3.6 % for NO_2 and are generally below 1 % for CH_2O and O_3, yet with statistically significant changes. The net contribution of climate change, assessed through the statistical relationship between interannual variations of pollutant anomalies and anomalies in climate parameters, showed that climate change accounts for less than 10 % of the total pollutants' variability. On average, this contribution is approximately 5 % for NO_2, 3 % for O_3, and only about 1 % for CH_2O.***

Conclusions. ***The obtained results indicate that the development of air pollution reduction strategies and air quality improvement should primarily focus on reducing direct anthropogenic emissions and their negative impact on public health and ecosystems. However, the role of climate change should also be considered as a significant factor in the formation of atmospheric pollution.***

Keywords: ***nitrogen dioxide, formaldehyde, tropospheric ozone, air pollution, additive model, climate change.***

Background

For more than half a century, air pollution has been among the most serious issues related to human anthropogenic activities, with numerous consequences for the environment, public health, and the economy (Rentschler & Leonova, 2023). Despite global efforts to mitigate the effects and reduce pollutant emissions, the issue of air quality will remain one of the key environmental challenges for a long time (Vilcins et al., 2024).

In Ukraine, air pollution is a relevant problem due to both the historical development of industry and the increasing number of vehicles in recent decades. Russia's aggression against Ukraine has become an additional factor contributing to the emergence of war-related emission sources and further atmospheric pollution. The existing air quality problems in Ukraine are widely discussed in scientific publications, addressing all spatial scales: general trends across the country (e.g., Rychak et al., 2021; Savenets et al., 2023a; Yatsenko et al., 2018), regional changes (e.g., Chugai, & Safranov, 2020; Melniichuk et al., 2022), and detailed analyses for specific cities (e.g., Kuzyk et al., 2024; Shevchenko et al., 2015; Turos et al., 2018). With the full-scale invasion, there were conducted new studies on air quality changes during the war (Malytska et al., 2024; Savenets et al., 2023b; Zhang et al., 2023). However, almost all of these studies rely on satellite remote sensing data without analyzing ground-level concentrations of pollutants.

Alongside atmospheric air pollution, the Earth's climate system is also undergoing significant changes. Climate change, driven by anthropogenic impact on the atmospheric chemical composition, also directly affects this composition through numerous feedbacks. Consequently, air pollution is also influenced by climate change (Jacob & Winner, 2009). Atmospheric pollution in the context of climate change is characterized by complex interdependencies that are extremely difficult to assess accurately (Dewan, & Lakhani, 2022). At the same time, evaluating the extent of climate change's impact on air pollution is a crucial task. Ignoring this factor and focusing solely on emission sources may lead to inaccurate future projections and the development of ineffective strategies.

Research on the relationship between anthropogenic air pollution and climate change focuses on two aspects: identifying key climatic parameters and physico-chemical processes, and determining the contribution and trends of future changes in pollutant concentrations. On one hand, climate change is most evident in rising air temperatures, which influence the rate of chemical transformations in the atmosphere (Cheng et al., 2007). This factor has been shown to be significant for certain pollutants, such as nitrogen dioxide (NO_2) (Syafei et al., 2019), tropospheric ozone (O_3) (Doherty et al., 2013), and formaldehyde (CH_2O) (Wu et al., 2023). However, depending on the region and pollutants, the dependence on rising air temperature is not always evident. For example, Elminir (2005) emphasized on the role of wind changes and relative humidity in shaping air pollution; however, over shorter time scales. Depending on the pollutants, different factors are expected to play a dominant role in the future, particularly changes in emissions themselves (Shen et al., 2021), temperature variations affecting chemical reactions (Doherty et al., 2013), and secondary pollutant formation (Wu et al., 2023). The estimated contribution of climate change to air pollution varies across different regions but is generally considered to be less than 10 % (Brasseur et al., 2006).

Given the uncertainties in assessing the dependence of air pollution on climate change, this study is aimed to determine the net contribution of climate change to pollutant concentrations over Ukraine using statistical time series analysis methods. The paper consists of the following parts: (1) a methodological section presenting the selected time series decomposition model and describing the input data; (2) an analysis of the results with a step-by-step breakdown of time series components; and (3) a discussion of the findings.

Methods

The model for time series decomposition of pollutants' concentrations. Among the various approaches to statistical time series decomposition, an additive model has been selected due to its relative ease of implementation and practical applicability to meteorological and climate data (Chang et al., 2021; Moreno-Carbonell et al., 2020). The additive model assumes that a time series can be decomposed into separate components step by step, isolating individual elements of the series. The sum of these components, along with an unexplained term (so-called statistical "noise"), allows for obtaining the series value at a given moment in time t. The convenience of using the additive model for meteorological and climate series is explained by the fact that meteorological parameters (as well as atmospheric pollution parameters) are always shaped by the influence of high-frequency processes (daily and annual cycles), some interannual trends, and low-frequency components (long-term variability). In climate data analysis, it is common practice to work with anomalies, i.e., the differences between actual values and the climatic normal (Arguez, & Vose, 2011; Wang et al., 2023). Essentially, anomaly calculation is already the first step in time series decomposition, where the contribution of a higher-frequency mean component is extracted from the actual values. The general form of the additive model for a time series element at a given moment t is as follows (formula 1):

$$X_t = Xseas_t + Xtrend_t + Xint_t + \varepsilon, \quad (1)$$

where X_t – the element (actual value) of the time series at time t; $Xseas_t$ – the contribution of the high-frequency (seasonal) component at time t; $Xtrend_t$ – the contribution determined by the presence of a trend; $Xint_t$ – the contribution of the low-frequency (interannual) component; ε – an unexplained term of the time series, usually "white noise" if all statistically significant components have been extracted.

The decomposition of the time series components occurs step by step in the order presented in formula 1. First, high-frequency (seasonal) fluctuations are assessed by calculating daily or monthly mean values and constructing an annual cycle. For the purpose of this study, monthly data were used; in this case, the high-frequency component and annual cycle are determined based on monthly averages. The average value for each of the 12 months is calculated using the arithmetic mean formula. Thus, the contribution of the high-frequency component of the time series for month i at time t is calculated using formula 2:

$$Xseas_t^i = \frac{1}{n}\sum_{t=1}^{n} X_t^i, \quad (2)$$

where $Xseas_t^i$ – the multi-year average value for month i; X_t^i – the actual value for month i at time t; n – the total number of values for month i.

In the case of air pollution, pollutant concentrations exhibit intra-annual fluctuations influenced by both the seasonal variability of meteorological conditions and changes in emission volumes throughout the year (e.g., the heating season, etc.). When calculating the $Xseas$ component the contributions of both factors affecting intra-annual air pollution variability are considered simultaneously. A similar procedure is applied to the time series of climate parameters and pollutant emissions. For further time series decomposition, it is necessary to transition from actual values to anomaly time series by subtracting the $Xseas$ component:

$$X'^i_t = X_t^i - Xseas_t^i, \quad (3)$$

where X'^i_t – anomaly for month i.

Determining the contribution of the high-frequency component from time series and transitioning to anomalies allows for the calculation of the trend component. In the case of air pollution, trends in concentration changes are largely driven by variations in pollutant emissions. Therefore, extracting the trend is a necessary step in transitioning to new anomalies that exclude emission source activity and are primarily shaped by interannual climate variability. Based on the calculated anomalies X' linear trends in the time series were computed, and their contribution was determined (formula 4). Additionally, it is important to account for the possibility of a nonlinear relationship between pollutant concentrations (X) in cities and anthropogenic emissions (E). This is achieved by analyzing the regression dependence of X'_t from E'_t after extracting linear trends. Thus, formula 4 for computing anomalies without trend contributions and interannual dependence on anthropogenic emission sources takes the following form:

$$X''_t = X'_t - (at + b) - cE'_t, \quad (4)$$

where X'_t – anomaly of pollutant concentration; E'_t – anomaly of the volume of anthropogenic emission sources; X''_t – anomaly excluding the trend contribution and interannual dependence on anthropogenic emissions; a і b – linear trend coefficients; c – regression coefficient for the interannual dependence of concentrations on anthropogenic emissions. The component $(at + b + cE'_t)$ corresponds to the component $Xtrend_t$ in formula 1.

It is important to note that we performed a checking procedure for the presence of trends with different directions during the study period. This is crucial for correctly excluding the contribution of anthropogenic emission sources from the time series of pollutant concentrations. However, no such cases were recorded in the selected cities during the study period.

Formula 4 is not applied to climate parameters because their trends directly reflect the impact of climate change.

After computing X''_t for pollutants, the next step is to assess the contribution of climate change to pollutant concentrations. The time series X''_t has been decomposed and cleared of intra-annual variations and anthropogenic emission dependencies. That is, for pollutants X''_t correspond $(Xint_t + \varepsilon)$ from formula 1. The analysis of dependence on climate parameters was conducted using multiple regression, where the predictors are anomalies of air temperature, wind speed, and precipitation sums, while the dependent variable is X''_t (pollutant concentration anomalies excluding trend contributions and interannual dependence on anthropogenic emissions). The general form of the dependence on K number of climate parameters is as follows:

$$X''_t = \beta_0 + \sum_{k=1}^{K} \beta_k \, CL'^{k}_t + \varepsilon, \quad (5)$$

where X''_t – anomaly excluding the trend contribution and interannual dependence on anthropogenic emissions; CL'^{k}_t – anomaly of climate parameter k; β_k – regression coefficient of climate parameter k; β_0 – intercept term in the multiple regression equation.

The time series decomposition can be extended further to find the long-term fluctuations, transitioning to the residual component, which corresponds to "white noise". However, further decomposition goes beyond the scope of the presented study. In this study, the unexplained component ε is used to determine the percentage of variability that remains after extracting all time series components and accounting for key climate indicators.

Input data and processing methodology. To implement the calculations using the additive model of time series decomposition, monthly data from three different types were used for the period from 2003 to 2021: ground-level concentrations of pollutants, emissions of pollutants, and climatic parameters. The observation period was chosen based on available data from the reanalysis services of the Copernicus Atmospheric Monitoring Service (CAMS, 2025; Inness et al., 2019).

Pollutants have different physicochemical properties and lifetimes in the atmosphere. As a result, the degree of influence of meteorological and climatic conditions on them will vary significantly depending on the chosen substances for the study. In the presented research, more chemically active substances have been selected, the concentrations of which in the atmosphere significantly depend on environmental conditions: nitrogen dioxide (NO_2), formaldehyde (CH_2O), and tropospheric (ground-level) ozone (O_3). NO_2 is one of the most common pollutants, emitted by most anthropogenic sources, and serves as an indicator of overall air quality (Moshammer et al., 2020). NO_2 is always included in monitoring programs regardless of the country or approach. The choice of CH_2O is due to the need to include an organic compound (with a carbon molecule in its structure), which is quite common due to anthropogenic emissions, but with a stronger dependence on meteorological conditions than, for example, carbon monoxide (CO) (Miller et al., 2008). O_3 is the only substance in the list that is not directly emitted but is formed as a result of photochemical reactions in the atmosphere in the presence of precursors. Having a highly harmful effect on human health and ecosystems, O_3 is also a mandatory substance in monitoring programs for air pollution worldwide (Zhang et al., 2019). It is clear that the formation of O_3 due to photochemical processes in the atmosphere indicates a dependence of concentration formation on meteorological conditions, and therefore, a potential strong signal for studying the dependence on climate change.

The data for the monthly concentrations of pollutants were taken from the global reanalysis ECMWF Atmospheric Composition Reanalysis 4 (EAC4) of the CAMS service (EAC4, 2025; Inness et al., 2019), where ground-level concentrations are represented as a mixture ratio [kg/kg] in a model grid with a horizontal resolution of 0.75° in both latitude and longitude. For convenience, the concentrations of pollutants were converted to [μg/kg]. To calculate the average concentration in the studied city, all grid cells covering the city area were averaged. For remote natural areas, data were taken from a single grid cell.

The pollutant emissions were estimated based on the global emission inventory data from CAMS (CAMS emissions, 2025; Granier et al., 2019). Since the aim of the conducted research was to determine the role of the climatic component, it was necessary to separate anthropogenic emissions (which need to be considered and accounted for) from biogenic emissions (which contribute to the concentration depending on climate change and therefore should not be excluded from the time series). Anthropogenic emissions are represented with a horizontal resolution of 0.1° in both latitude and longitude. To link the formed concentrations with pollutant emissions, the values of anthropogenic emissions were summed across all grid cells in the inventory that intersected with the grid cells designated for pollutants. In this way, emissions were calculated for the entire city area or the entire section of natural areas. Emission data in inventories represent the flux of a substance and are therefore usually expressed in [$kg \cdot m^{-2} \cdot s^{-1}$]. For ease of analysis, all anthropogenic emissions were converted into tons per month [$t \cdot month^{-1}$].

For studying the relationship with climatic parameters, three key indicators were chosen, which significantly influence the selected pollutants (Seroji et al., 2004): (1) air temperature, which determines the rate of chemical transformation in the atmosphere; (2) wind speed, which affects accumulation and transport; and (3) precipitation, which determines the intensity of wet deposition. It was decided not to use moisture parameters due to their strong statistical dependence on air temperature and precipitation. This would distort the process of determining statistically reliable results and the role of individual climatic parameters during multiple regression analysis. Climate data were taken from the ERA5 reanalysis (ERA5, 2025; Hersbach et al., 2023). Air temperature values were converted from [K] to [°C], and precipitation values from [m] to [mm] and integrated over the month.

To study the contribution of climate change to the formation of pollutant concentrations, three large cities (Kyiv, Odesa, and Lviv) and three locations in natural reserves, which are among the cleanest areas in Ukraine (Askania-Nova, Medobory, and Shatsk Lakes), were selected. The initial idea of using data from even cleaner mountainous regions of Ukraine – the Carpathian and Crimean Mountains – was discarded during the data processing due to the unreliability and low accuracy of the reanalysis and CAMS inventory data over areas with complex terrain.

Calculation of the contribution of time series components to the total variability. At each stage of extracting components of the time series related to different processes using formulas 2, 4, and 5, the coefficients of determination (R^2) were calculated. The R^2 value ranges from

0 to 1 and reflects the proportion of variability of the studied process within the total variability of the series. For convenience in interpreting the results, this proportion was expressed as a percentage [%]. Clearly, if at the first stage of time series decomposition (calculation of seasonal variability) R^2 indicates the proportion of the total variability, then at subsequent stages, it indicates the proportion of the residual variability (since the contribution of the process is subtracted and anomalies are found). To convert R^2 from residual variability to total variability, the corresponding R^2 at the decomposition stage i was multiplied by the unexplained term that remained after the decomposition at all previous stages. Thus, for the calculation of the contribution of interannual trends, the formula used was $R_i^2 \cdot (1 - R_{i-1}^2)$, and for the interannual dependence on climatic parameters, it was $R_i^2 \cdot (1 - R_{i-1}^2 - R_{i-2}^2)$. Therefore, when recalculating R^2 for all the studied processes, their sum, including the unexplained part, equals 100%, meaning $R^2 = 1$.

At all stages of the calculation, statistical significance was verified using the student's t-test with a 95 % confidence level for the result.

Results

Seasonal variability of pollutants. The calculation of average multi-year values showed that seasonal variability plays a key role in the variability of monthly average concentrations of pollutants both in cities and in pristine natural areas. In fig. 1, the role of seasonal (intra-annual) fluctuations is clearly observed for the example of Kyiv and the "Medobory" Nature Reserve. The intra-annual fluctuations of the studied pollutants depend both on the seasonality of meteorological conditions (especially the increased role of solar radiation in the formation of CH_2O and O_3 in the summer) and on the seasonality in activity of specific emission sources (particularly the change in NO_2 from additional emissions during the heating season).

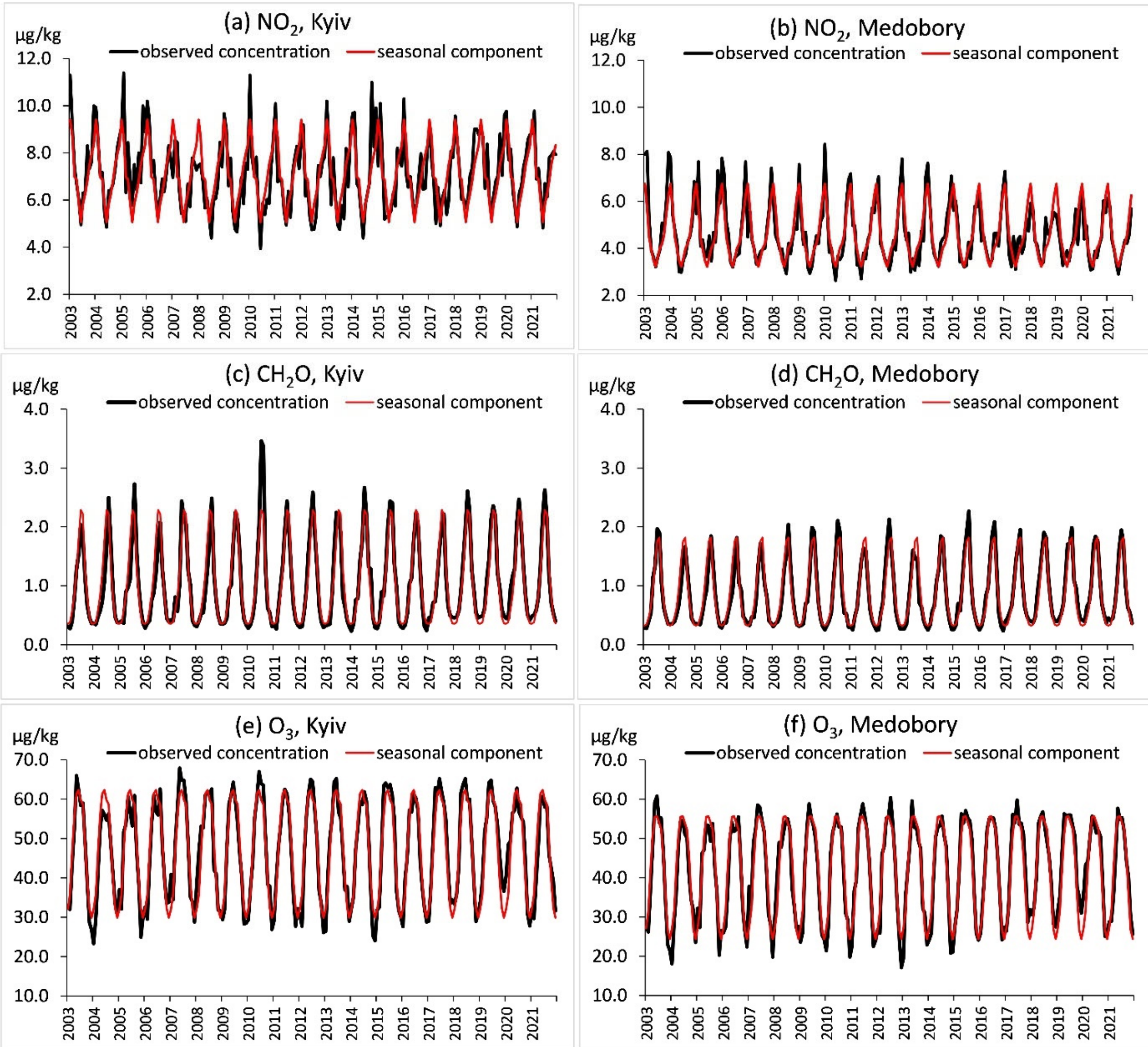

Fig. 1. Time series of the observed pollutants' concentrations and determined seasonal component on the example of Kyiv (a, c, e) and Medobory (b, d, f)

For CH_2O and O_3, whose formation and removal depends on the seasonality of solar radiation, the R^2 of the seasonal component ranges from 89 % to 93 %. CH_2O shows slightly better seasonal variability in cleaner natural reserves, with an R^2 around 93 %. The lowest R^2 values were observed in Kyiv (89.7 %).

The clarity of O_3 seasonal variability depends more on the latitudinal distribution than on differences in the volume of anthropogenic emissions. The farther south the area is located, the more clearly O_3 seasonal variability is observed, primarily due to the higher intensity of solar radiation reaching the Earth's surface. As a result, the R^2 for O_3 seasonal variability exceeds 92.6 % in Odesa and Askania-Nova, while in Lviv and the Shatsk Lakes, it is 3 % lower, at 89.6 %.

Among the studied components, seasonal variability is most poorly observed in NO_2 time series. Furthermore, in cities, the seasonality worsens. While in natural areas, the R^2 for NO_2 ranged from 70.3 % in Askania-Nova to 74.1 % in Medobory, in cities it ranged from 61.5 % in Lviv to 67.4 % in Kyiv. Therefore, the presence of anthropogenic emission sources and higher concentrations of NO_2 lead to a deterioration in the clarity of intra-annual fluctuations.

Trends in pollutants changes and their dependence on emissions at interannual scale. The calculation of concentration anomalies for pollutants allowed for the analysis of the presence of interannual trends. Fig. 2 displays the trends for all the studied pollutants and areas, where statistically significant trends are highlighted in green, while insignificant ones are marked in yellow.

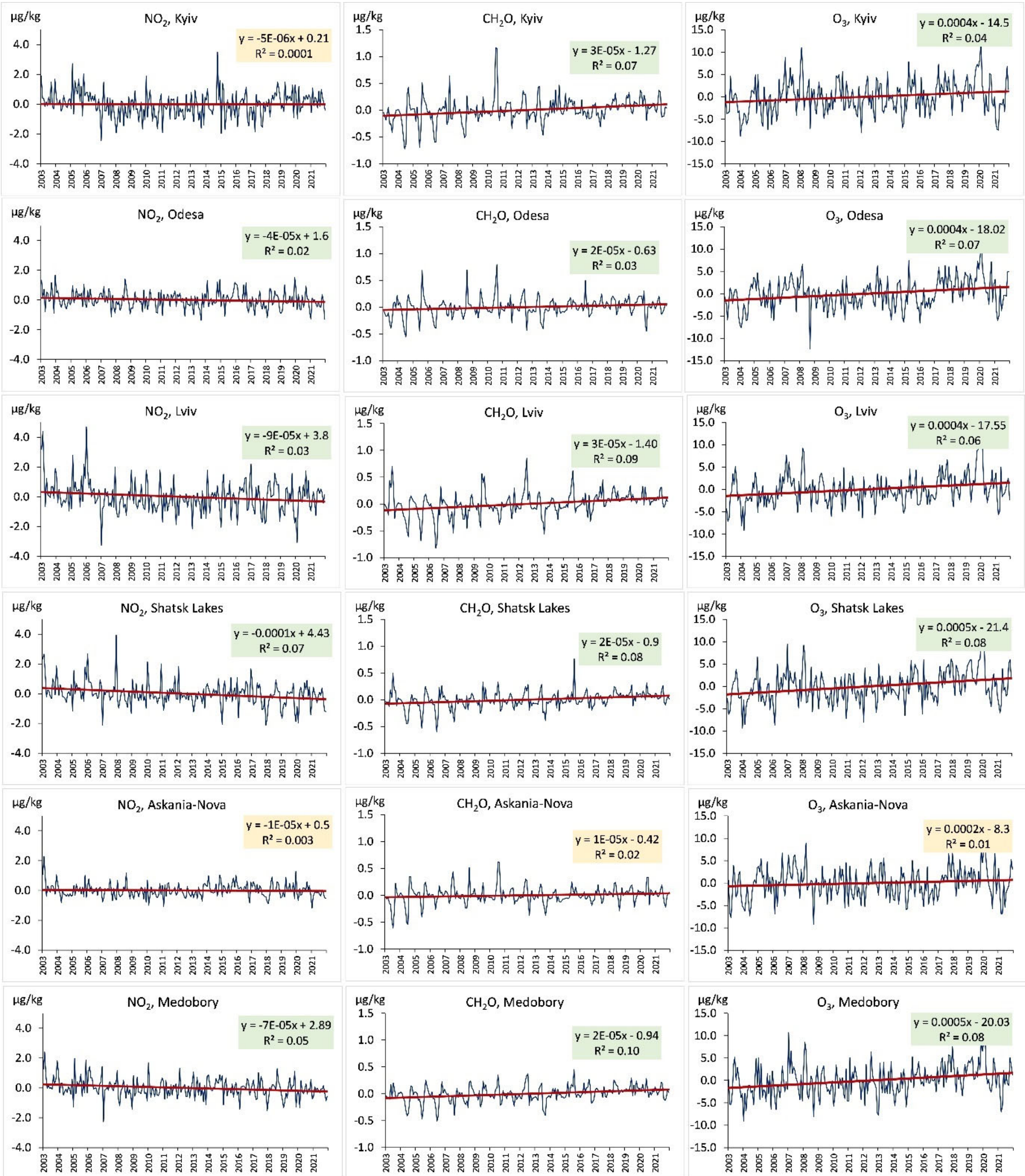

Fig. 2. Trends of anomaly time series for NO_2 (first column), CH_2O (second column) and O_3 (third column) for all study locations

For the overwhelming majority of time series, interannual trends are observed, although most of them are relatively weak, yet statistically significant. Askania-Nova is the only location where no significant trends were found for all the studied pollutants. Additionally, the absence of trends is characteristic for NO_2 in Kyiv.

NO_2 is the only pollutant whose concentrations decrease in the case of significant trends (see fig. 2, first column). The magnitude of these trends is as follows: in Lviv, the R^2 of the NO_2 trend, when adjusted for total variability, is around 3.6%. The trends are somewhat less intense in natural zones: about 2.1 % in the Shatsk Lakes and 1.2 % in the Medobory Nature Reserve. The smallest contribution from significant NO_2 trends is observed in Odesa, where R^2 accounts for only 0.6 % of the total variability in the series.

The concentrations of CH_2O are increasing in all studied locations except for Askania-Nova. The most intense increase is observed in Lviv, where the R^2 of the trend reaches approximately 1.1 % of the total variability of the series. In Shatsk Lakes and Medobory, the R^2 values for CH_2O trends reach 0.8 % and 0.9 %, respectively.

Similarly to CH_2O, the concentrations of O_3 also increased over the studied period in all locations except for Askania-Nova. The R^2 values of the trends increased in Medobory and Shatsk Lakes by approximately 0.6 % and 0.9 %, respectively. In urban areas, the most significant increase in O_3 was recorded in Lviv, with an R^2 value of approximately 0.7 % of the total variability of the time series. The values in Odesa and Kyiv were lower, amounting to 0.5 % and 0.3 %, respectively, but they remained statistically significant over the studied period.

Thus, between 2003 and 2021, there was a slight decrease in NO_2 levels and an increase in CH_2O and O_3 concentrations. The trends for NO_2 and CH_2O are driven by the growth of anthropogenic emissions and are well aligned with them. However, the role of precursor emissions in the interannual trends of O_3 requires further investigation, as O_3 is not directly emitted but is significantly influenced by anthropogenic emissions of other pollutants.

It is important to note that emission inventories from CAMS reanalyses do not always fully capture the entire spectrum of anthropogenic emissions in Ukrainian cities due to underreported emission volumes and the limitations of emission assessments in Ukraine (Savenets et al., 2024). CAMS estimates partially rely on national inventories. Therefore, the reduction in NO_2 levels in major cities may reflect broader background trends. Based on the available time series, it is impossible to determine this with certainty. In such a case, the trends for NO_2 may not necessarily be negative but rather statistically insignificant.

Contribution of interannual variability of climatic parameters. The absence of distinct seasonal fluctuations and interannual trends in the time series allows for the calculation of anomalies in which only interannual variations remain as the deterministic component. Such anomalies enable the assessment of the interannual dependence on climatic parameters, which helps determine whether climate makes a significant contribution to the variability of air pollutants. Using equation 5, multiple regression analysis was performed, and the significance of the impact of climatic parameters on air pollutants was tested.

Firstly, it is important to note the absence of significant β_0 (i.e., the intercept of the multiple regression equation). Secondly, a significant net contribution of climate change to the formation of pollutant concentrations was identified at all studied locations except for NO_2 in Odesa. Table 1 presents the results of the multiple regression analysis. Specifically, the nature of the relationship between climatic parameters and pollutants is illustrated, where a red upward arrow indicates an increase in pollutant concentrations with an increase in a specific climatic parameter, while a green downward arrow indicates a decrease in pollutant concentrations as the climatic parameter increases.

Table 1

Characteristics of statistical dependence (multiple regression) between pollutant concentrations and climatic parameters

Location	Air temperature	Wind speed	Precipitation	R^2 of dependence	Contribution (%)
NO_2					
Kyiv	–	↓	↓	0.12	3.94
Odesa	–	–	–	0.03	–
Lviv	↓	↓	↓	0.27	9.47
Shatsk Lakes	↓	↓	↓	0.22	5.85
Askania-Nova	↓	↓	–	0.05	1.56
Medobory	↓	↓	↓	0.22	5.45
CH_2O					
Kyiv	↑	–	↓	0.16	1.56
Odesa	↑	–	–	0.11	0.86
Lviv	↑	↓	–	0.10	0.67
Shatsk Lakes	↑	–	↓	0.15	0.90
Askania-Nova	↑	–	–	0.17	1.17
Medobory	↑	–	↓	0.15	0.97
O_3					
Kyiv	↑	–	↑	0.35	2.86
Odesa	↑	–	–	0.16	1.08
Lviv	↑	–	↑	0.37	3.61
Shatsk Lakes	↑	–	↑	0.42	4.05
Askania-Nova	↑	↓	–	0.30	2.20
Medobory	↑	–	↑	0.31	2.35

↑ concentrations increase if climate variable increase
↓ concentrations decrease if climate variable increase
– insignificant relationships

Overall, the role of climatic parameters in shaping pollutant concentrations varies from 0.7 % to 9.5 %. The strongest relationship was observed for NO_2, while the weakest was for CH_2O. Among the selected pollutants, interannual changes in air temperature (which influences chemical transformations) and precipitation (which affects wet deposition) showed a significantly stronger impact compared to wind speed (which determines accumulation conditions), except in the case of NO_2. At the same time, wind speed consistently demonstrated a uniform relationship, with increasing wind speed leading to a decrease in pollutant concentrations. In contrast, air temperature and precipitation exhibited variable relationships depending on the specific pollutant.

The contribution of climatic parameters to the total variability of NO_2 time series is the highest among the studied pollutants. Except for Odesa, it ranges from 1.6 % in Askania-Nova to 9.5 % in Lviv. No clear pattern distinguishes urban areas from natural territories. An increase in precipitation (and consequently, an increase in wet deposition intensity) and an increase in wind speed (enhancing dispersion) expectedly lead to a decrease in NO_2 concentrations. Regarding air temperature, its interannual increase results in a decrease in NO_2 concentrations due to the intensification of chemical transformation processes, where NO_2 acts as a precursor to other compounds.

The role of climatic parameters in shaping the interannual variations of ground-level O_3 ranges from approximately 1.1 % in Odesa to 4.1 % in the Shatsk Lakes region. The dependence appears weaker in southern locations, where O_3 levels are generally higher. An increase in air temperature leads to an increase in O_3 concentrations due to the enhanced intensity of its formation from precursors. On an interannual scale, wind speed has almost no impact on O_3 formation, with the only significant dependence observed in Askania-Nova. Notably, O_3 concentrations increase on an interannual scale with rising precipitation levels. This dependence does not reflect a direct impact but rather the creation of specific conditions favorable for O_3 accumulation during periods of higher precipitation. These conditions include an increased influx of volatile organic compounds (VOCs) from moist soil and vegetation after rainfall, which serve as O_3 precursors.

Interannual changes in climatic parameters have the smallest impact on CH_2O concentrations, contributing between 0.9 % in Odesa and the Shatsk Lakes to 1.6 % in Kyiv. Air temperature is the only variable whose interannual changes affect CH_2O concentrations across all studied locations. Higher air temperatures lead to increased CH_2O levels, primarily due to enhanced chemical formation. Wet deposition plays an important role in reducing CH_2O concentrations, but a significant dependence on precipitation was found only in Kyiv, as well as in the Shatsk Lakes and Medobory nature reserves. Wind speed was only significant in Lviv, where decreasing wind speeds correlate with rising CH_2O concentrations.

General characteristics of time series components and their residual part. After extracting the main components of the time series and assessing the dependence of pollutant concentrations on interannual climatic variations, a certain unexplained residual part remains. Of course, this residual unexplained component could be further analyzed to identify long-term fluctuations and other dependencies until reaching "white noise", but such an approach falls outside the scope of this study.

As a result of the analysis, the largest residual component is observed for NO_2, ranging from 19.2 % to 33.4 % (Table 2). In contrast, the residual part is significantly smaller for CH_2O (Table 3) and O_3 (Table 4), amounting to 5.3–8.0 % and 5.2–6.1 %, respectively.

Table 2

The contribution (in %) of NO_2 time series components to total variability

Location	Seasonal variability	Trends and interannual dependence on emissions	Interannual dependence on climate variables	Residual part (unexplained)
Kyiv	67.35	–	3.94	28.71
Odesa	65.93	0.64	–	33.43
Lviv	61.54	3.55	9.47	25.44
Shatsk Lakes	71.36	2.05	5.85	20.74
Askania-Nova	70.29	–	1.56	28.15
Medobory	74.09	1.23	5.45	19.23

Table 3

The contribution (in %) of CH_2O time series components to total variability

Location	Seasonal variability	Trends and interannual dependence on emissions	Interannual dependence on climate variables	Residual part (unexplained)
Kyiv	89.68	0.74	1.56	8.02
Odesa	92.10	0.24	0.86	6.80
Lviv	92.16	1.06	0.67	6.11
Shatsk Lakes	93.00	0.79	0.90	5.31
Askania-Nova	92.98	–	1.17	5.85
Medobory	92.60	0.89	0.97	5.54

Table 4

The contribution (in %) of O_3 time series components to total variability

Location	Seasonal variability	Trends and interannual dependence on emissions	Interannual dependence on climate variables	Residual part (unexplained)
Kyiv	91.43	0.32	2.86	5.39
Odesa	92.69	0.51	1.08	5.72
Lviv	89.60	0.67	3.61	6.12
Shatsk Lakes	89.57	0.87	4.05	5.51
Askania-Nova	92.58	–	2.20	5.22
Medobory	91.80	0.64	2.35	5.21

A key feature is that, on average, the residual (unexplained) variability in pollutant concentrations is slightly higher in urban areas than in natural regions. These differences primarily stem from seasonal variability in pollutant concentrations. This is well justified, as emissions in cities are often non-deterministic and chaotic throughout the year, leading to greater residual variability compared to natural areas.

Overall, the seasonal variability of CH_2O and O_3 is well-defined and explains most of the variability in pollutant concentrations. In contrast, NO_2 exhibits smaller intra-annual variations, while its trends are more pronounced, and its interannual dependence on climatic variability is more evident.

Thus, the pure impact of climate change on pollutant concentrations represents a relatively small part of total variability, but it remains significant for identification purposes. Across the studied region, this contribution does not exceed 10 %, averaging 5 % for NO_2, 3 % for O_3, and only about 1 % for CH_2O.

Discussion and conclusions

The contribution established in studies, where interannual variability of climatic parameters determines the variability of atmospheric air pollution, is relatively small in magnitude but significant. While some scientists emphasize that the dependence of air pollution on climate change should become more evident in the future (Hong et al., 2019), most publications still point to the complexity of connections within the climate system and their manifestation in various atmospheric processes, making it difficult to link the consequences of climate change to air pollution (Dewan, & Lakhani, 2022). Clearly, analyzing only time series of pollutants is insufficient to account for all possible connections. This approach is more of a simplified statistical model for determining the overall share of variability rather than a final assessment. Theoretically, the contribution of climate change to air pollution could be greater if the increasing frequency of wildfires and dust storms in the future is taken into account.

It is important to assess projections of future changes in precipitation frequency and atmospheric boundary layer parameters; however, the accuracy of these estimates in climate models remains in question (Jacob, & Winner, 2009). Some studies indicate the decisive influence of wind characteristics (Shen et al., 2021), whereas the estimates obtained in this study suggest that wind does not play a determining role, unlike precipitation and air temperature, especially for O_3 and CH_2O. The further rise in air temperature is expected to worsen air quality, but Giorgi & Meleux (2007) emphasizes the non-linearity of atmospheric interactions, where additional precursor emissions may have a reverse effect due to chemical transformations and removal processes.

The contribution values of climate change obtained in this study, particularly for O_3, align well with Brasseur et al. (2006), where the contribution of climate to concentrations was determined to range from -8 % to 10 %. The calculations in this study showed values ranging from 1 % to 4 %. As highlighted by Murazaki and Hess (2006), air temperature has a determining influence, but our study also identified the impact of precipitation.

The well-established importance of air temperature changes for NO_2 (Syafei et al., 2019) was also confirmed in this study. Atmospheric precipitation and wind speed were also identified as significant factors shaping the interannual variations of NO_2. It is worth noting that some researchers consider climate-induced changes in NO_2 emissions to be more influential than the direct impact on already formed concentrations (Shen et al., 2021).

For CH_2O, significant dependencies on air temperature and precipitation were obtained. The role of thermal conditions has been previously emphasized, particularly due to its secondary formation under higher air temperatures in the future (Wu et al., 2023). Wind dependence was characteristic only for Lviv; however, Chauhan et al. (2025) highlighted the secondary importance of wind parameters after air temperature. It is entirely possible that such manifestations have regional specificities, being significant in some areas while absent in others. In any case, studying the predominant role of specific climatic parameters in the context of climate change requires more complex analyses beyond statistical assessment.

Overall, despite the relatively small contribution of climate change to the formation of pollutant concentrations, studying their interactions is crucial for planning development (Afifa et al., 2024). Further expansion of similar research is essential for assessing the implications for public health (de Sario et al., 2013), as changes in pollutant concentrations under climate change conditions can increase population mortality rates (Orru et al., 2013).

The formation of pollutant concentrations in any territory of Ukraine significantly depends on the anthropogenic factor, which largely determines both the seasonal variability of pollution and interannual trends. The study of three pollutants – NO_2, CH_2O, and O_3 – whose physicochemical properties contribute to a stronger dependence on meteorological conditions, revealed the dominant role of seasonal fluctuations in shaping concentration variability. While for NO_2, intra-annual variability accounts for 61 to 74 % of total variability, for CH_2O and O_3, it is predominantly above 90 %. During the study period, there were no extremely high trend coefficients or dependencies on interannual emission trends, with NO_2 concentrations showing a tendency to decrease.

The net impact of climate change, assessed based on interannual dependence on the variability of key climatic parameters (air temperature, wind speed, and precipitation), constitutes a relatively small but statistically significant portion of variability, with values reaching up to 10 % of total variability. On average, this contribution is about 5 % for NO_2, 3 % for O_3, and only around 1 % for CH_2O. The obtained results indicate that urban air quality management should primarily focus on reducing pollutant emissions and adapting urban areas to minimize pollution impacts on public health. At the same time, the presence of a small but statistically significant dependence of pollution on climate change should be considered when planning the reconstruction and development of industrial enterprises and implementing optimization measures to reduce emissions from mobile sources. Such considerations in the future will help eliminate the factor of air quality deterioration due to climate change and allow a direct focus on measures to reduce pollutant emissions.

Authors contribution: Mykhailo Savenets – conceptualization, supervision, methodology, writing; Sofiia Krainyk – data validation, computations; Daria Hrama, Maryna Rudas, Oksana Skliar – data preparation, computations.

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Михайло САВЕНЕЦЬ[1], канд. геогр. наук, ст. дослідник
ORCID ID: 0000-0001-9429-6209,
e-mail: savenets@uhmi.org.ua

Софія КРАЙНИК[1], інженер
ORCID ID: 0009-0004-6299-0983
e-mail: sofiakrajnik7@gmail.com

Дар'я ГРАМА[2], студентка
e-mail: aeweriss@gmail.com

Марина РУДАС[2], студентка
e-mail: rudas22ed@gmail.com

Оксана СКЛЯР[2], студентка
e-mail: oksanasklar16@gmail.com

[1]Український гідрометеорологічний інститут ДСНС України та НАН України, Київ, Україна
[2]Київський національний університет імені Тараса Шевченка, Київ, Україна

СТАТИСТИЧНЕ ОЦІНЮВАННЯ ЧИСТОГО ВНЕСКУ ЗМІНИ КЛІМАТУ У ФОРМУВАННЯ КОНЦЕНТРАЦІЙ ЗАБРУДНЮВАЛЬНИХ РЕЧОВИН В АТМОСФЕРНОМУ ПОВІТРІ НАД ТЕРИТОРІЄЮ УКРАЇНИ

В с т у п . ***Забруднення атмосферного повітря та зміна клімату є одними з основних чинників негативного антропогенного впливу на довкілля. Варіативність забруднювальних речовин більшою мірою залежить від викидів, проте залишається недостатньо вивченою роль зміни клімату у формуванні концентрацій, що важливо враховувати при довготерміновому плануванні поліпшення якості атмосферного повітря та стратегії зменшення викидів. У даній роботі представлено аналіз чистого внеску зміни клімату у формування концентрацій шкідливих домішок на основі застосування статистичного підходу до розкладання часових рядів.***

М е т о д и . ***В основі досліджень лежать місячні дані викидів і концентрацій діоксиду азоту (NO_2), фомальдегіду (CH_2O) та тропосферного (приземного) озону (O_3) з реаналізів Copernicus Atmospheric Monitoring Service (CAMS) за період з 2003 до 2021 р., а також дані температури повітря, швидкості вітру і кількості опадів із реаналізу ERA5. Застосування адитивної моделі дало змогу розкласти часові ряди концентрацій на сезонну (внутрішньорічну) складову, міжрічні тренди та міжрічну залежність варіативності концентрацій NO_2, CH_2O й O_3 від мінливості кліматичних параметрів.***

Р е з у л ь т а т и . ***Сезонна мінливість концентрацій, що залежить як від зміни метеорологічних умов, так і відмінності у викидах забруднювальних речовин, пояснює від 61 до 74 % загальної варіативності NO_2, та близько 90 % CH_2O й O_3. Міжрічні тенденції досліджуваних забруднювальних речовин, що залежать від зміни антропогенного навантаження, становлять від 0,6 до 3,6 % для NO_2 та переважно менше 1 % для CH_2O й O_3, проте зі статистично значущими змінами. Чистий внесок зміни клімату, оцінений через статистичну залежність міжрічних варіацій аномалій часових рядів забруднювальних речовин з аномаліями кліматичних параметрів, показав, що зміна клімату визначає менше 10 % загальної варіативності концентрацій забруднювальних речовин. У середньому цей показник сягає близько 5 % для NO_2, 3 % для O_3 та лише близько 1 % для CH_2O.***

В и с н о в к и . ***Отримані результати вказують на те, що розроблення стратегій зменшення викидів забруднювальних речовин та поліпшення якості атмосферного повітря, передусім має передбачати зменшення прямих антропогенних викидів і їх негативного впливу на здоров'я населення й екосистеми. Проте роль зміни клімату також має бути врахована як значущий чинник у формуванні атмосферного забруднення.***

К л ю ч о в і с л о в а : ***діоксид азоту, формальдегід, тропосферний озон, забруднення атмосфери, адитивна модель, зміна клімату.***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

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