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SIMULATION OF AIR POLLUTION IN KYIV CAUSED BY WILDFIRES IN THE FALL OF 2024

Introduction. Air pollution in Kyiv is frequently influenced by wildfires occurring outside the city, although their contributions are not always readily identifiable.

Problem Statement. Quantitative analysis and prediction of wildfire-induced air pollution require accurate assessment of emission rates, which can be derived from satellite data such as MODIS fire products.

Purpose. This study aims to implement a methodology for assessing air pollution following wildfires by combining existing parameterizations of pollutant emissions with state-of-the-art atmospheric transport models, and to validate this methodology using measurements collected during a real air pollution episode in Kyiv in September 2024.

Materials and Methods. MODIS fire products and established methods for their processing have been employed. Atmospheric transport has been simulated with the dispersion module of the RODOS system. Meteorological input is taken from the WRF-Ukraine numerical weather prediction system. Observational data on PM_{2.5} concentrations in Kyiv have been used for validation. Lagrangian atmospheric transport modeling methods have been employed.

Results. A methodology for estimating wildfire emission rates has been developed by integrating parameterizations of particulate matter emissions from individual MODIS fire detections with methods for evaluating time-integrated fire radiative energy. The resulting emission estimates have been used to simulate PM_{2.5} pollution in Kyiv during the real pollution episode on 20 September 2024. The model

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has skillfully reproduced both the plume arrival time and the temporal evolution of $PM_{2.5}$ concentrations in comparison with measurements. The 24-hour average wildfire-induced $PM_{2.5}$ concentrations have ranged from 11.6 to $34.7 \mu\text{g}/\text{m}^3$ across different parts of Kyiv, exceeding the regulatory maximum permissible value of $25 \mu\text{g}/\text{m}^3$.

Conclusions. The developed methodology has demonstrated its suitability for operational forecasting of wildfire-related air contamination and for retrospective analyses of historical pollution episodes, enabling quantification of wildfire contributions to observed air quality degradation.

Keywords: air pollution, atmospheric dispersion, wildfires, RODOS, MODIS, $PM_{2.5}$.

Episodes of heavy air pollution regularly happen in Kyiv, and this causes considerable public concerns [1–3]. Different researchers studied various aspects of the problem of air pollution in Kyiv [4–9]. As shown by several investigators, in many cases, especially during dry periods, heavy pollution episodes with increased levels of particulate matter (PM) were caused by wildfires outside cities [6, 7]. The ongoing war led to an even worsening of the impact of wildfires on the problem of air pollution in Ukraine and in Kyiv [9]. Because on the one hand, air pollution in cities is created by many sources, and on the other — because pollutants could be brought by wind from wildfires, located quite far from cities, the impact of wildfires was not easily recognized in many particular cases.

Forecasting of air pollution episodes including those created by wildfires is important for timely warning of population regarding hazardous situations. Uncovering the role of wildfires in case they influence air pollution is equally important for better understanding the reasons for unfavorable conditions and for adequate planning of measures to reduce the number of harmful air pollution episodes. Satellite programs effectively monitor wildfires, and the respective resources are available [10]. The satellite data, describing regions encompassed by wildfires and their radiative power are however insufficient to forecast air pollution. The emission inventories are to be first derived from the available information and secondly, atmospheric transport of combustion products is to be simulated. The goal of the present study is thus to implement a methodology for the assessment of air pollution following wildfires by combining available parameterizations of pollutant emission with the state-of-art models

of atmospheric transport and to validate it against measurements collected in real-case episode of air pollution in Kyiv in September 2024.

ALGORITHM OF EMISSION ESTIMATION

In this work estimates of PM emission during wildfires are based on processing satellite data regarding fires and burned areas of the Moderate Resolution Imaging Spectroradiometer (MODIS, [10]), as available on the Fire Information for Resource Management System (FIRMS) website, operated by NASA (https://firms.modaps.eosdis.nasa.gov/active_fire). Namely, the parameterization that relates the intensity of PM emission from a single MODIS detect of the wildfire to its fire radiative power FRP [MJ/s], proposed in [11] was used. Assuming 100% burned area per detect, the parameterization [11] reads as: $Q = 20[\text{g} \cdot \text{MJ}/\text{s}] \cdot FRP_{MD}$. Here Q [g/s] — is the emission rate of PM_{10} (PM with mean aerodynamic diameter less than $10 \mu\text{m}$) from the corresponding area, represented by MODIS detect, and FRP_{MD} is the FRP of the corresponding detect. To evaluate the average emission rate of continuous release over a particular time interval $(0, \tau)$ and from a certain area Ω , we must first evaluate the integral of FRP through the corresponding time interval and over the respective area, using discrete measurements of FRP from MODIS detects. To do that we use a simple representation of the observed FRP diurnal cycle proposed in [12]:

$$FRP(t) = FRP_{peak} \left[b + \exp \left(-\frac{(t-h)^2}{2\sigma^2} \right) \right], \quad (1)$$



Fig. 1. Locations of wildfires around Kyiv on September 20, 2024, according to MODIS data (rhombuses); pins symbols indicate measurement stations, which data were used in this study

where t [hrs] is time, the parameter h [hrs] corresponds to the local time at which the value of FRP reaches a maximum, FRP_{peak} [MJ/s]. The standard deviation σ [hrs] and nondimensional b are the other parameters of the distribution, described as follows. To estimate the values of b , σ , h the study [12] suggested their empirical dependencies on the ratio of measured FRP by satellites Terra and Aqua: $x = FRP(Terra)/FRP(Aqua)$ for a given region. Here FRP denotes the total sum of FRP from pixels over the whole simulation area Ω and summed over the considered time interval. According to the proposed parameterizations, the parameters of distribution (1) depend on x : $h = -1.23x + 14.57$, $\sigma = 3.89x + 1.03$, $b = 0.86x^2 - 0.52x + 0.08$. The value of FRP_{peak} is then evaluated with the next formula [13]:

$$FRP_{peak} = \frac{FRP_{tot}}{\sum_i \exp\left(-\frac{(t_i - h)^2}{2\sigma^2}\right)},$$

where t_i is the time of observation (typically $1 \leq i \leq 3$), FRP_{tot} is the sum of FRP from both satellites over all pixels within a given computational area, and the considered time interval.

Then, substituting all these formulas into (1), we can find the total fire radiation energy FRE [MJ], emitted from the area Ω :

$$FRE = \int_0^{\tau} FRP(t) dt. \quad (2)$$

We integrate the expression (2) numerically by the trapezium formulas with the time-step of 1 second.

Finally, we adapt the abovementioned parameterization [11] for the estimation of the release rate from the considered area Ω over the time interval $(0, \tau)$ in the following way:

$$Q = 20 \cdot FRE / \tau. \quad (3)$$

Here τ is in seconds.

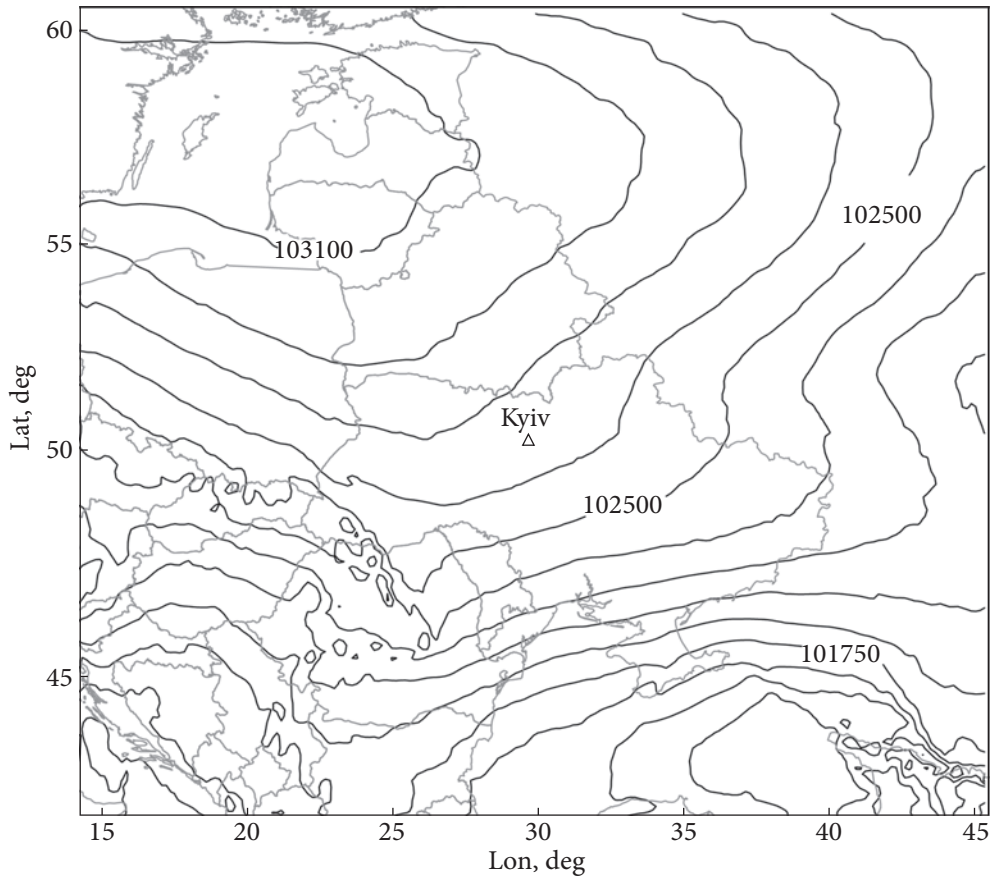


Fig. 2. Map of sea level pressure, analyzed by WRF-Ukraine NWP system for September 20, 2024, 00 h UTC. The interval between the isolines is 150 Pa

The described above algorithm was implemented in a software code that evaluates emission rates of PM, $Q(x_i, y_j, t_k)$, with time resolution $\tau = t_k - t_{k-1}$ (the default value is $\tau = 24$ h), from the grid cells of the sizes dx, dy , centered at points (x_i, y_j) , and covering the user-specified geographical area. The user specifies south-west and northeast corners of the grid, grid resolution dx, dy (in meters), start and end dates, and time of simulation.

MODEL CHAIN OF ATMOSPHERIC TRANSPORT

For the assessment of the atmospheric transport of air pollutants, created by wildfires, in this work, we used the atmospheric dispersion model LASAT

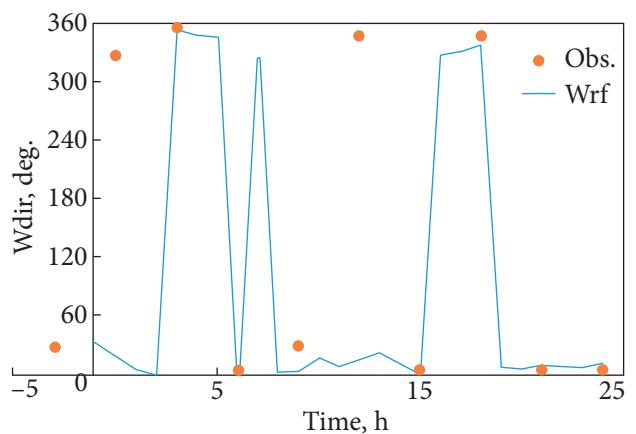


Fig. 3. Time dependence of observed and forecasted by WRF-Ukraine wind direction in Kyiv (Boryspil). Time is in hours starting from September 20, 2024, 00 UTC

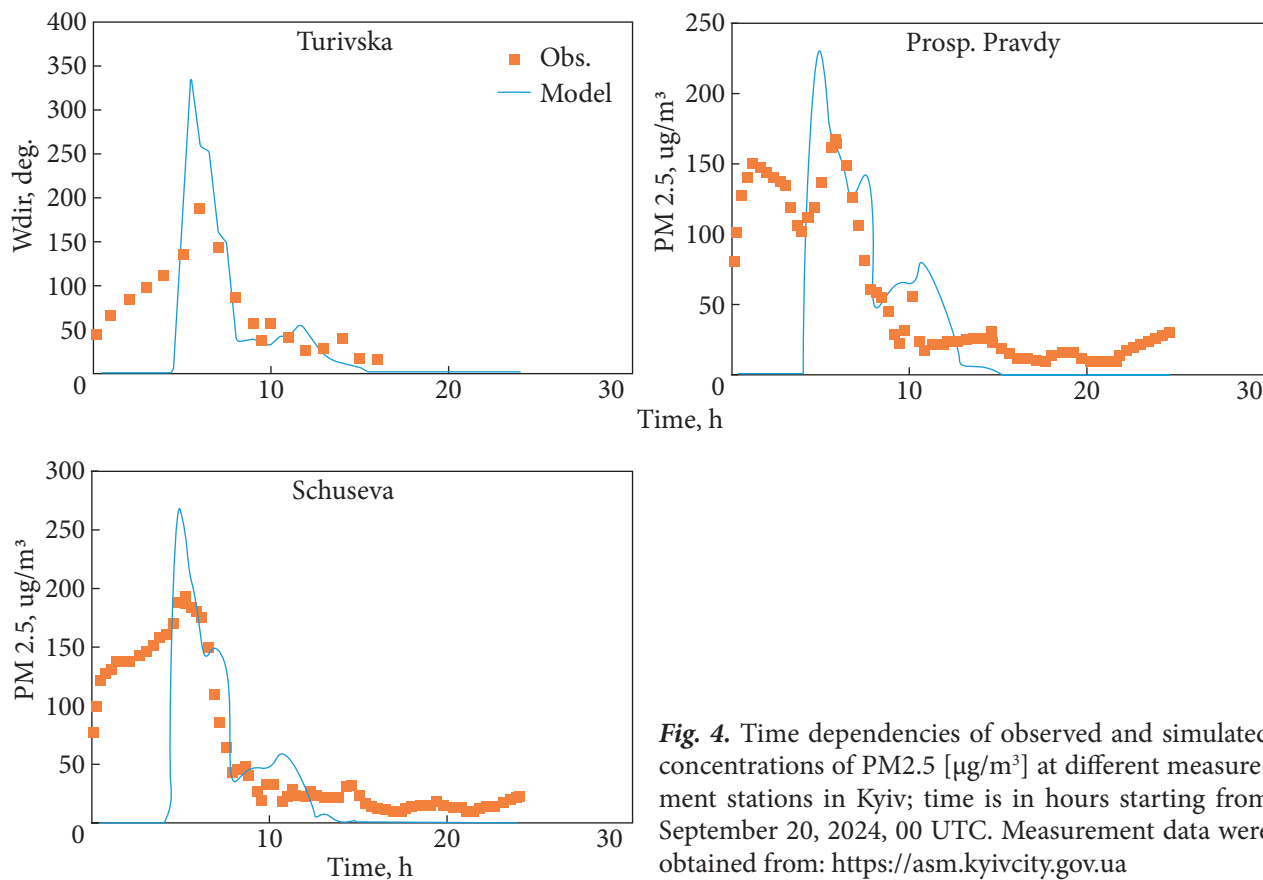


Fig. 4. Time dependencies of observed and simulated concentrations of PM_{2.5} [$\mu\text{g}/\text{m}^3$] at different measurement stations in Kyiv; time is in hours starting from September 20, 2024, 00 UTC. Measurement data were obtained from: <https://asm.kyivcity.gov.ua>

of the EU nuclear emergency response system RODOS [14]. This model was successfully used for the simulation of the atmospheric transport of radioactive pollutants created by wildfires in the Chernobyl Exclusion Zone [15]. The model requires input fields from the numerical weather prediction (NWP) model. For that purpose we used the operational forecasts of the WRF-Ukraine NWP system, functioning in the Ukrainian Hydrometeorological Center, and used for supply of the RODOS-Ukraine nuclear emergency response system with operational NWP data [16]. The operational forecasts are calculated on the sequence of nested grids [16]. In this work, we used results from the nested computational domain of WRF-Ukraine that covers the northwestern part of Ukraine (domain D02). The spatial resolution of this domain is 0.05° dec. deg. (154×167 computatio-

nal nodes in south-north and west-east directions respectively).

We evaluated the developed methodology against measurements collected during an air pollution episode that happened in Kyiv on September 20, 2024. On the morning of that day, Kyiv City Administration informed about the increased level of air pollution [3]. The possible indicated reason for that situation was wildfires in Kyiv Oblast. Therefore, we applied the described above model chain to analyze this episode quantitatively.

At first, we analyzed MODIS data of wildfires of September 20 between 0 h and 12 h UTC in the rectangle region having a size of 160×120 km around Kyiv. This region was subdivided into square computational cells, each having a size of 10×10 km². The active wildfires fell in a single computational cell, located approximately 60 km to the north of

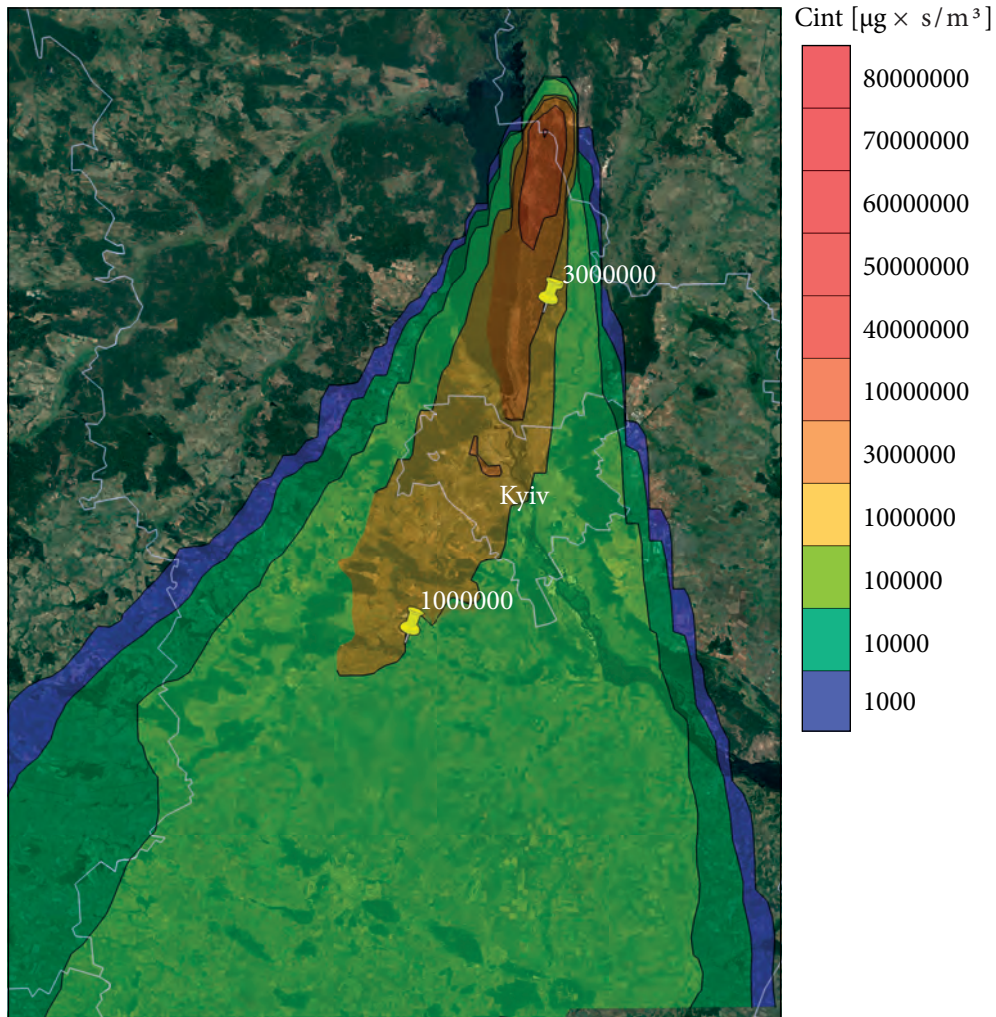


Fig. 5. Map of time-integrated concentration of PM2.5 [$\mu\text{g} \cdot \text{s}/\text{m}^3$], calculated between 20240920:00 h UTC and 20240921:00 h UTC. Values of isolines are shown on the right of the figure

Kyiv (Fig. 1). The total release rate of particulate matter PM10 from this cell, evaluated using formulas (1)—(3), was equal to 4.2 kg/s.

The atmospheric transport of fine particulate matter with a mean aerodynamic diameter less than or equal to 2.5 μm (PM2.5) was simulated using the described above model chain of the WRF-Ukraine NWP model and the atmospheric dispersion model of the RODOS system. The simulation was performed for the next 24 hours starting from the 20240920:00 h UTC. As the fraction of PM2.5 in

many cases consists $\approx 90\%$ of the total release of PM10 from the wildfires [17, 18], in the simulation we conservatively considered the release rate of PM2.5, equal to the above-evaluated release rate (4.2 kg/s between 0 h and 12 h UTC).

The meteorological conditions in Ukraine on 24 Sep. 2024 were influenced by a high-pressure system, centered over the Baltic Sea (Fig. 2). The high-pressure system extended to the east and south-east directions, leading to pressure rise and clear-sky, low-wind conditions. On the preceding

day (19 Sep. 2024) the dominant wind direction was NNE (Fig. 3). Wind direction changed on the next day (September 20) to the almost stable northern wind (Fig. 3). The dynamics of wind direction was skillfully forecasted by WRF-Ukraine NWP system (Fig. 3).

Time dynamics of simulated and observed concentrations of PM_{2.5} in Kyiv are shown in Fig. 4. Both measurements and simulations show maximum concentration between 5 and 6 h UTC. In contrast to measurements, simulated concentrations are zero at the beginning of the simulation, because pollution in Kyiv is created not only by the wildfire but also by other sources [8] that are not considered in this study. However, after the plume arrived in Kyiv at about 4.5 h UTC the simulated and observed concentrations were well correlated. By 16 h UTC concentrations reduce to zero due to a reduction in wind speed and the cease of wildfires and a correspondent reduction in pollutant flux into Kyiv from the upwind regions.

Figure 5 shows a map of the time-integrated concentration of PM_{2.5} [$\mu\text{g} \cdot \text{s}/\text{m}^3$] by the end of the simulation period (September 21, 00 h UTC). As it is seen from the data, presented on the map, the 24-h time-integrated concentration in Kyiv created by wildfires varies from 1E6 to 3E6 $\mu\text{g}\cdot\text{s}/\text{m}^3$. The corresponding time average concentration varies from 11.6 to 34.7 $\mu\text{g}/\text{m}^3$. Thus in part of Kyiv territory the PM_{2.5} concentrations created by this single wildfire exceeded the maximum permissible values of 25 $\mu\text{g}/\text{m}^3$, recommended by the European Union as a regulatory value for daily average concentrations of PM_{2.5} [19].

In this work, the methodology for the assessment of air pollution following wildfires was implemented by combining available parameterizations of pollutant emission with the state-of-art models of atmospheric transport. The methodology of emission rate estimation is based on the processing of publicly available MODIS fire pro-

ducts of the satellites Terra and Aqua. The parameterization originally proposed in [11], which established a connection between measured radiative power and emission rate of particulate matter was combined with the methods for assessment of time-integral fire radiative energy, using discrete data of MODIS detects. The obtained emissions estimates were then used as input to the atmospheric transport model of the RODOS system, which evaluated atmospheric transport of combustion products, using also operational numerical weather prediction data of the WRF-Ukraine meteorological forecasting system, operated by the Ukrainian Hydrometeorological Center. The developed method allows for a successful simulation of air pollution by PM_{2.5} in Kyiv during the real-case air pollution episode that happened on September 20, 2024. The time of arrival of the plume and the time series of PM_{2.5} concentrations in Kyiv were skillfully reproduced. The 24-hour average concentration of PM_{2.5} created by wildfires in different parts of Kyiv ranged from 11.6 to 34.7 $\mu\text{g}/\text{m}^3$, thus exceeding the regulatory maximum permissible value of 25 $\mu\text{g}/\text{m}^3$. The developed methodology could be used for operational forecasting of air contamination related to wildfires and for analysis of historical air pollution episodes concerning quantification of the role of wildfires in such events.

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МОДЕЛЮВАННЯ АТМОСФЕРНОГО ЗАБРУДНЕННЯ м. КИЇВ, СПРИЧИНЕНОГО ЛАНДШАФТНИМИ ПОЖЕЖАМИ ВОСЕНИ 2024 р.

Вступ. Забруднення повітря у Києві часто спричинено лісовими пожежами за межами міста, хоча їхній вплив не завжди легко розпізнати.

Проблематика. Кількісний аналіз та прогнозування забруднення повітря після лісових пожеж вимагає оцінки рівня викидів, яку можна отримати з супутникових даних, таких як дані *MODIS*.

Мета. Впровадити методологію оцінки забруднення повітря після лісових пожеж шляхом поєднання доступних параметризацій викидів забруднюючих речовин із сучасними моделями атмосферного переносу та перевірити її на основі вимірювань, зібраних під час реального епізоду забруднення повітря в Києві у вересні 2024 року.

Матеріали й методи. Використано дані *MODIS* щодо пожеж та методи їх обробки, застосовано модуль атмосферного розсіювання системи *RODOS*, дані чисельного прогнозування погоди системи *WRF*-Україна, дані вимірювань забруднення повітря *PM2.5* у Києві. Застосовано лагранжові методи моделювання дисперсії атмосферних забруднень.

Результати. Розроблено метод оцінки швидкості викидів шляхом поєднання параметризації викидів твердих частинок з одного детектування *MODIS* з методами оцінки інтегральної за часом радіаційної енергії пожежі. Отримані оцінки викидів було використано для моделювання забруднення повітря *PM2.5* у Києві під час реального епізоду забруднення повітря 20 вересня 2024 року. Час прибуття хмари та часові ряди концентрацій *PM2.5* успішно розраховані та узгоджувалися з вимірами. Середня 24-годинна концентрація *PM2.5*, міцностні лісовими пожежами в різних частинах Києва, коливалася від 11,6 до 34,7 мкг/м³, що перевищує нормативне гранично допустиме значення 25 мкг/м³.

Висновки. Запропоновану методику можна використовувати для оперативного прогнозування забруднення повітря, пов'язаного з лісовими пожежами, та для аналізу історичних епізодів забруднення повітря щодо кількісної оцінки ролі лісових пожеж у таких подіях.

Ключові слова: забруднення повітря, атмосферне перенесення, лісові пожежі, *RODOS*, *MODIS*, *PM2.5*.