Transboundary Air Pollution in the Krakow Agglomeration Using the HYSPLIT Model

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Abstract

The study aims to analyze the measurement data of PM10 particulate matter in the Krakow agglomeration. It develops a model of the backward trajectory of air masses to determine whether and to what extent natural phenomena, such as forest fires outside Poland, affect the level of air pollution.
The article describes the process of pollutant dispersion in the Earth's atmosphere and the principles of air monitoring in the Krakow agglomeration. The study uses 2022 measurement data from ten monitoring stations of the Chief Inspectorate of Environmental Protection in the Krakow agglomeration. Two periods of increased PM10 particulate matter were selected. On the basis of the HYSPLIT software, which uses backward air trajectories, the influx of transboundary pollution was simulated. Then, by analyzing the FIRMS fire information system, an attempt was made to document that the pollution sources considered were of natural origin and that human activity did not in any way determine the emissions and their magnitude.

Keywords: *particulate pollution, air pollution modeling, air quality assessment, environmental monitoring, forest fires*

1. Introduction

The Earth's atmosphere is the outer gaseous envelope whose function protects living beings from rapid changes in temperature, electromagnetic radiation, and the fall of meteoroids. The composition of the air depends on many factors and can change depending on the climate, season, and even time of day. Air is a homogeneous mixture of gases characterized by its lack of odor, color, and taste and poor solubility in water [5]. With the influx of various substances, both from natural and anthropogenic sources, there is a change in the natural composition of the atmosphere. The primary origin of anthropogenic sources includes electricity and heat production, domestic furnaces, industry, transportation, and agriculture. In contrast, sources of natural origin include volcanic eruptions, forests, savannahs, steppe fires, rock and soil erosion, and biological processes. Among the substances emitted into the ambient air are nitrogen oxides, sulfur oxides, carbon monoxide, tropospheric ozone, volatile organic compounds, PAHs, and, above all, PM10 (particles smaller than 10 μm in diameter) and PM2.5 (very fine particles less than 2.5 μm in diameter). These pollutants can directly affect the environment, such as by causing smog, and indirectly by accumulating toxic compounds in living organisms [1, 6].

Pollutants emitted into the environment are dispersed. Three factors that affect the dispersion of pollutants include meteorological, topographical, and technical factors. Undoubtedly, meteorological factors have a decisive influence, as climatic parameters are subject to the most significant changes due to atmospheric turbulence, vertical temperature gradient, wind action, mixing zone thickness, and precipitation [9].

The air quality measurement system plays a crucial role in identifying pollution. Poland's measurements are carried out as part of the State Environmental Monitoring program to provide reliable information on the state of the environment. Multi-year programs have been developed by the Chief Inspectorate of Environmental Protection and approved by the Climate Minister. Environmental monitoring is carried out in all voivodships. The number of permanent measuring stations depends on the number of inhabitants, the type and the sources of emissions, and exceedances of permissible concentrations. The measurement stations are located according to their purpose and the area of representativeness of the results obtained in terms of the type of station. A distinction is made between urban, suburban, traffic, industrial, non-urban, and regional background stations [4].

The selection of the location of the measurement points involves multistage planning and compliance with strict criteria described in the Environmental Ministry Regulation of September 13, 2012, on the assessment of the levels of substances in the air. The ordinance specifies location criteria on a micro- and macro-scale. First, in the case of PM10, special care is taken to ensure that the airflow within a few meters around the air intake is not impeded by other obstacles in the form of shrubs, trees, and buildings, and in the case of traffic stations at least 0.5 meters from buildings and 25 meters from the edge of the main intersections. Another crucial requirement is the elevation or height of the air intake station within the range between 1.5 and 4 meters above ground level. The design of the air intake station is also crucial for preventing the re-intake of the discharged air. For the latter scale regarding PM10, the station's location should be selected in terms of the study areas with the highest levels of substances to which the population is exposed during the averaging period of the results, as well as for those areas where the limit, tar-

Tab. 1. The minimum number of continuous measurement points required to assess the air quality of PM10 particulate matter [8]

Tab. 1. Minimalna liczba stałych punktów pomiarowych wymagana na potrzeby oceny jakości powietrza dla pyłu zawieszonego PM10 [8]

Zone Population (in Thousands)	Minimum Number of Continuous Measurement Points	
	The level of substances in the air exceeds the upper threshold estimate	The level of substances in the air between the upper and lower thresholds estimates
	PM10 Particulate Matter	PM10 Particulate Matter
0 – 249	2	1
250 – 499	3	2
500 – 749	3	2
750 – 999	4	2
1000 – 1499	6	3
1500 – 1999	7	3
2000 – 2749	8	4
2750 – 3749	10	4
3750 – 3749	11	6
4750 – 5999	13	6
> 6000	15	7

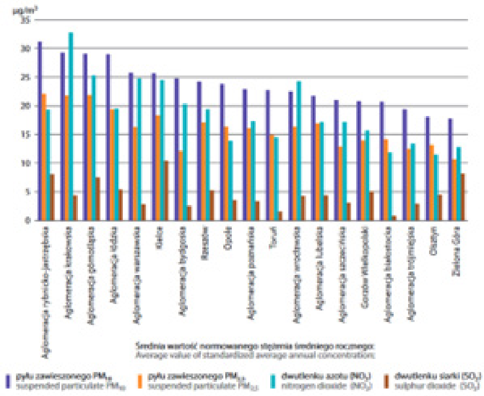

Fig. 1. PM2.5, PM10, NO_2, and SO_2 in selected regions of Poland in 2020 [2]

Fig. 1. PM2.5, PM10, NO_2 i SO_2 w wybranych regionach Polski w 2020 r. [2]

get and long-term goal levels of substances in the air are established. The minimum number of fixed measurement points to measure PM10 particulate matter depends on the number of residents (a directly proportional relationship) (Table 1). Additionally, the results must represent the place of the impact of transportation or industry. In the case of industrial impact, the location of at least one measurement point should be on the leeward side of the installation in the vicinity of a nearby residential area [8].

Particulate pollution is hazardous to the environment. Particulates adversely affect the health of humans and animals, disrupt the physiological functions of plants, and lead to the destruction of building materials. Under conditions of temperature inversion and high concentrations of sulfur dioxide, winter smog can form. This phenomenon irritates the respiratory tract and circulatory system of living organisms. During an outbreak of acid smog in London in 1952, more than 4,000 people died within a few days. The WHO confirms the negative impact of particulate matter that causes many diseases and disorders. The more urbanized and industrialized the area, the more significant the impact of pollution [3].

An example of an urbanized area is the Krakow agglomeration, which is struggling with many environmental problems [7]. Despite the ban on burning solid fuels, elevated and exceeded concentrations of particulate pollutants are observed in Krakow due to the lack of restrictions in the surrounding communities. Local industry and transport contribute a large share of dust emissions [1, 4]. According to the 2021 Regional Development of Poland Report by the Central Statistical Office, dust emissions from establishments particularly detrimental to clean air were observed in 37 large cities in 2020. Figure 1 presents the values of the average annual concentrations of air pollutants in Poland. The highest concentrations of PM10 particulate matter, right after the Rybnik-Jastrzębska agglomeration, were recorded in the Krakow agglomeration (29 μg/m³) [2].

2. Purpose and Methods

The study aimed to analyze the measurement data of PM10 particulate matter in the Krakow agglomeration and to build a model of the backward trajectories of air masses to determine the contribution of natural phenomena to air pollution.

The study used 2022 measurement data from ten Chief Inspectorate of Environmental Protection monitoring stations in the Krakow agglomeration. During data analysis, two periods lasting several days that exceeded limit levels or above-average concentrations of PM10 particulate matter outside the heating period were selected. The monitoring stations, both automatic and manual, are shown in Figure 2. If a station made measurements using both methods, measurements performed using the manual method were included in the analysis of daily averages due to their higher precision. Among the measurement stations were [11]:

1) Krakow urban background station, Bujaka Street (international station code: PL0501A), with the coordinates: 50.010575 N and 19.949189 E and an altitude of 223 m above sea level. The station measures PM10, PM2.5, benzo(a)pyrene, arsenic, benzo(anthracene), benzo(b)fluoranthene, benzo(j)fluoranthene, cadmium, dibenzo(a,h)anthracene, indeno(1, 2, 3-cd)pyrene, nickel, in PM10 with a 24-hour averaging time and PM10, nitric oxide, nitrogen dioxide, nitrogen oxides, ozone, sulfur dioxide, benzene with a 1-hour averaging time;

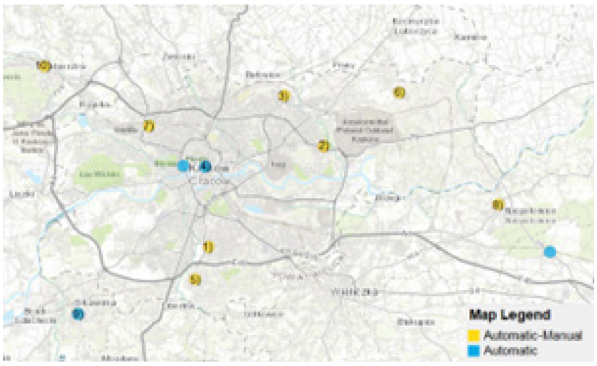

Fig. 2. Map of measuring stations in the Krakow agglomeration [11]
Fig. 2. Mapa stacji monitoringu w aglomeracji krakowskiej [11]

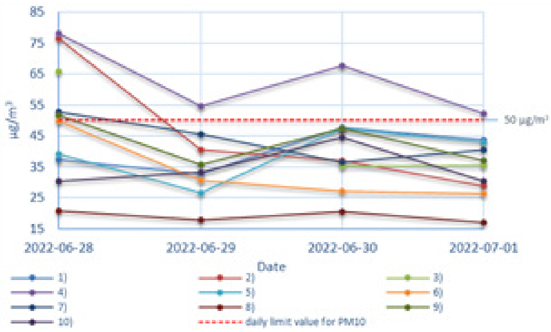

Fig. 3. Measurement data from PM10 particulate matter monitoring stations in period one at 12:00 pm [compiled from 11]
Fig. 3. Dane pomiarowe ze stacji monitoringu pyłów zawieszonych PM10 w epizodzie pierwszym dla godziny 12:00 [opracowanie na podstawie 11]

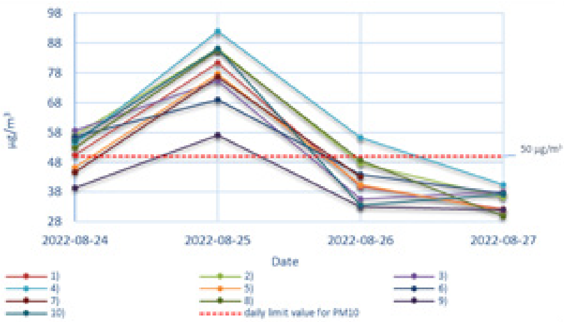

Fig. 4. Measurement data from PM10 particulate matter monitoring stations in period two at 12:00 pm [compiled from 11]
Fig. 4. Dane pomiarowe ze stacji monitoringu pyłów zawieszonych PM10 w epizodzie drugim dla godziny 12:00 [opracowanie na podstawie 11]

2) Krakow industrial station, Bulwarowa Street (international station code: PL0039A), with the coordinates 50.069308 N and 20.053492 E and an altitude of 195 m above sea level. The station measures PM10, benzo(a)pyrene, arsenic, cadmium, nickel, and lead in PM10 with a 24-hour averaging time and PM10, PM2.5, benzene, carbon monoxide, nitrogen oxide, sulfur dioxide with a 1-hour averaging time;

3) Krakow urban background station, Piastow Estate (international code of the station: PL0642A), with the coordinates 50.098508 N and 20.018269 E and an altitude of 239 m above sea level. The station measures PM10 particulate matter and benzo(a)pyrene in PM10 with a 24-hour averaging time and PM10 with a 1-hour averaging time;

4) Krakow transportation station, Dietla Street (international station code: PL0641A) with coordinates 50.057447 N and 19.946008 E and altitude 209 m above sea level. The station measures PM10 particulate matter, nitrogen oxide, nitrogen dioxide, nitrogen oxides with a 1-hour averaging time;

5) Krakow urban background station, Swoszowice District (international code of the station: PL0735A) with coordinates 49.991442 N and 19.936792 E and an altitude of 236 m above sea level. The station measures PM10 particulate matter and benzo(a)pyrene in PM10 with a 24-hour averaging time and PM10 with a 1-hour averaging time;

6) Krakow industrial station, Wadow Estate (international station code: PL0670A) with coordinates 50.100569 N and 20.122561 E and an altitude of 218 m above sea level. The station measures PM10, benzo(a)pyrene, arsenic, cadmium, nickel, lead in PM10 with a 24-hour averaging time and PM10 with a 1-hour averaging time;

7) Krakow urban background station, Zloty Rog Street (international code of the station: PL0643A) with coordinates 50.081197 N and 19.895358 E and an altitude of 218 m above sea level. The station measures PM10 particulate matter and benzo(a)pyrene in PM10 with a 24-hour averaging time and PM10 with a 1-hour averaging time;

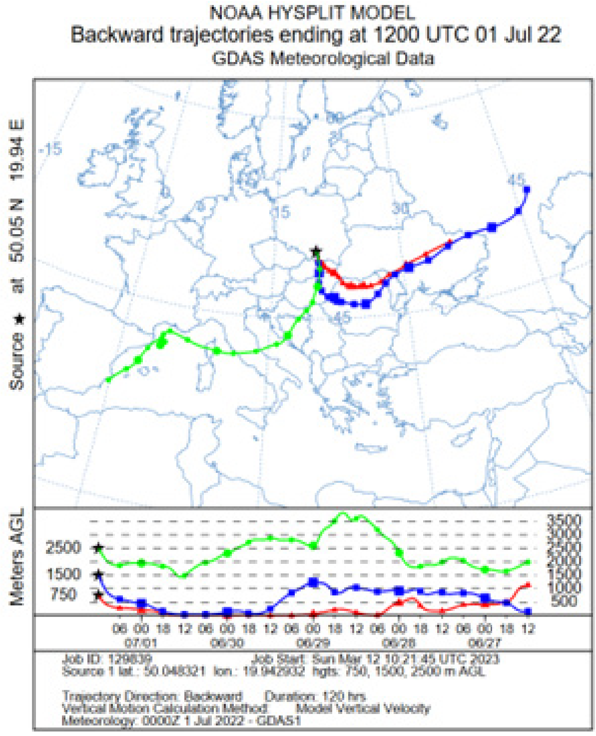

Fig. 5. HYSPLIT model of backward trajectories of air masses from June 27 to July 1, 2022 [compiled from 12]

Fig. 5. Model HYSPLIT wstecznych trajektorii mas powietrza w okresie od 27 czerwca 2022 r. do 1 lipca 2022 r. [opracowanie na podstawie 12]

Fig. 6. FIRMS data on fires during the first period of increased concentrations of PM10 particulate matter between August 16–20, 2022 [10]

Fig. 6. Dane FIRMS o pożarach w czasie pierwszego epizodu zwiększonego stężenia pyłów zawieszonych PM10 w okresie od 16 sierpnia 2022 r. do 20 sierpnia 2022 r. [10]

8) Niepolomice urban background station, 3 May Street (international station code: PM0125A) with coordinates 50.035117 N and 20.212689 E and altitude 201 m above sea level. The station measures PM10 particulate matter and benzo(a)pyrene in PM10 with a 24-hour averaging time and PM10 with 1-hour averaging time;

9) Skawina urban background station, Ogrody Estate (international station code: PL0273A) with coordinates: 49.971047 N and 19.830422 E and an altitude of 225 m above sea level. The station measures nitrogen oxide, carbon dioxide, oxides of nitrogen, PM10 particulate matter, sulfur dioxide, and benzene with a 1-hour averaging time.

10) Zabierzow urban background station, Wapienna Street (international station code: PL0728A) with coordinates: 50.116028 N and 19.800639 E and an altitude of 238 m above sea level. The station measures PM10 particulate matter and benzo(a)pyrene in PM10 with a 24-hour averaging time and PM10 with a 1-hour averaging time.

Daily average measurement data for the periods used for the analysis:

1. From June 28 to July 1, 2022, when daily values of PM10 particulate matter from 15.1 μg/m³ to 47.7 μg/m³ were recorded;
2. From August 24–27, 2022, when daily values of suspended particulate matter from 25.2 μg/m³ to 59.4 μg/m³ were recorded, and the 24-hour limit level of 50 μg/m³ was exceeded at the station numbers: 1), 2), 3), 4), 7), 10).

The measured values of the individual monitoring stations in period one at noon are shown in Figure 3. On June 28, 2022, notably increased PM10 values were observed at stations 2) and 4), reaching values of more than 75 μg/m³. Analyzing historical weather data on that day on the Weather Spark platform (https://pl.weatherspark.com), the following weather parameters were observed in Krakow: almost cloudless skies and a temperature of 30°C and at noon, an average wind speed of 7.49 km/h, measured at the height of 10 meters [13]. Such weather conditions and the lack of precipitation favored the occurrence of high concentrations of air pollution.

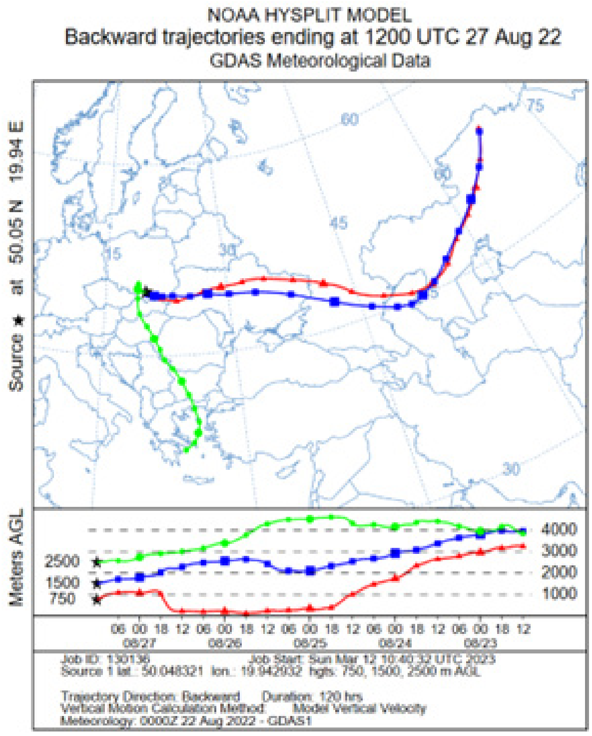

Fig. 7. HYSPLIT model of backward air trajectories from August 23–27, 2022 [compiled from 12]

Fig. 7. Model HYSPLIT wstecznych trajektorii powietrza w okresie od 23 sierpnia 2022 r. do 27 sierpnia 2022 r. [opracowanie na podstawie 12]

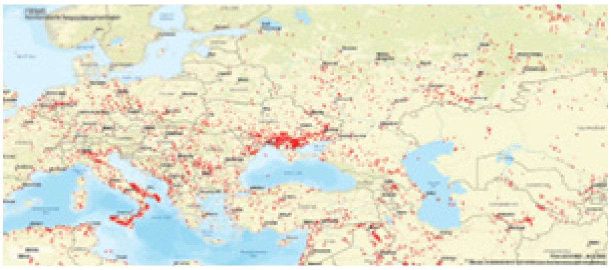

Fig. 8. Map of FIRMS data on fires during the second period of increased concentrations of PM10 particulate matter from August 24–28, 2022 [10]

Fig. 8. Mapa danych FIRMS o pożarach w czasie drugiego epizodu zwiększonego stężenia pyłów zawieszonych PM10 w okresie od 24 sierpnia 2022 r. do 28 sierpnia 2022 r. [10]

The highest concentrations of PM10 dust were recorded on August 25, 2022. Upon analyzing data from the mentioned weather platform, the day was characterized by partial cloud cover, an air temperature that reached 26°C, and an average wind speed of 7.41 km/h [13]. As in the first period, the weather conditions also contributed to the high PM10 values. In the case of period two, equally increased values were observed at all stations at noon, as confirmed by Figure 4.

Based on the HYSPLIT software (Hybrid Single-Particle Lagrangian Integrated Trajectories, https://www.ready.noaa.gov/hypub-bin/trajsrc.pl), using backward air trajectories, the influx of transboundary pollutants was simulated in selected periods of elevated PM10 concentrations. Based on European Commission guidelines, the simulation included: 5-day backward trajectories of air masses, measurement data for noon, a simulation of three elevations: 750 m above sea level, 1500 m above sea level, 2500 m above sea level, and a vertical wind speed profile.

The next step was to analyze NASA's Fire Information for Resource Management System (FIRMS) to identify whether the prevailing fires during the period affected the measurements. This type of analysis allows us to determine whether elevated concentrations of PM10 particulate matter in the Krakow metropolitan area were of natural or anthropogenic origin.

3. Results and Discussion

During the analysis of the first HYSPLIT model of backward trajectories of air masses from June 28 to July 1, 2022 (Fig. 5), an influx of masses was observed from the south of Poland. For preset heights of 750 m above sea level and 1500 m above sea level, trajectories could be observed coming from Ukraine via Romania and Slovakia. However, in the case of the highest altitude (2,500 meters above sea level), the masses were coming from Spain, through the French coast and Italy, to the Balkan Peninsula and Slovakia.

Observing the map of fires during the first period, shown in Figure 6, despite individual fires in most countries, special attention is drawn to the fact that there is a large outbreak of fires in Italy and Ukraine. A simulation of incoming air masses shows that natural phenomena in these areas indirectly affect the degree of air pollution in the Krakow metropolitan area.

Figure 7 presents the HYSPLIT model for August 23–27, 2022. In the second analyzed period, air masses were observed from the east and the south. For the simulation's preset altitude of 750 m above sea level and 1500 m above sea level, the masses came from Kazakhstan, Russia, and Ukraine. The air masses at 2500 m above sea level came from southeastern Europe. Therefore, it can be concluded with a high probability that dust from areas on Poland's eastern border may have entered the Krakow agglomeration along with the influx of air.

Considering the influx of air masses, let us note the large fire outbreak in Ukraine and southern Europe. In the example of the fire map shown in Figure 8, it is also possible to see the spread of fires in most countries between August 24–28, 2022. It is estimated that the influx of pollutants from the fires indirectly contributed to the increase in air pollution in the Krakow metropolitan area during this period. In the first and second periods, the sources were natural phenomena, and emissions and their magnitude were not determined by human factors.

4. Conclusions

The study made it possible to assess the daytime variability of meteorological conditions and document that in the analyzed periods of increased PM10 pollution in the Krakow agglomeration, i.e., from June 2 to July 1, 2022, and from August 24 to 27, 2022, the pollution sources considered were of natural origin, as a result of spreading fires in eastern Europe. Human activity in no way determined the fact of the emissions themselves and their magnitude.

In the first period, a simulation with the HYSPLIT software shows retrograde trajectories from Ukraine, through Romania and Slovakia, and from Spain, through the French coast, Italy, to the Balkan Peninsula, and Slovakia. However, the second period shows an influx of air masses from Kazakhstan, Russia, and Ukraine, as well as from the southern part of Europe. As mentioned above, the increase in air pollution in the Krakow agglomeration was correlated with the spread of fires in the regions.

Undoubtedly, air monitoring in Poland provides reliable information on the state of the environment, giving residents a sense of security and allowing them to respond to the presence of pollution, both from natural and anthropogenic sources. Measurements of monitoring stations in 2022 confirmed the problem of PM10 pollution above the daily limit value, so the developed models can be used in the future to predict the impact, even distant natural phenomena far from the surveyed area.

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Transgraniczne zanieczyszczenie powietrza w aglomeracji krakowskiej z zastosowaniem modelu HYSPLIT

Celem badań była analiza danych pomiarowych pyłów zawieszonych PM10 na terenie aglomeracji krakowskiej oraz wykonanie modelu trajektorii wstecznych mas powietrza w celu określenia, czy i w jakim stopniu zjawiska naturalne, takie jak pożary lasów poza granicami Polski, wpływają na stopień zanieczyszczenia powietrza.
W artykule opisano proces dyspersji zanieczyszczeń w atmosferze ziemskiej oraz zasady monitoringu powietrza w aglomeracji krakowskiej. Do opracowania posłużono się danymi pomiarowymi z 2022 r. z dziesięciu stacji monitoringu Głównego Inspektoratu Ochrony Środowiska, znajdujących się na terenie aglomeracji krakowskiej, gdzie wytypowano dwa epizody zwiększonego stopnia zanieczyszczenia pyłami zawieszonymi PM10. Bazując na oprogramowaniu HYSPLIT, który wykorzystuje wsteczne trajektorie powietrza, przeprowadzono symulację napływu zanieczyszczeń transgranicznych. Następnie analizując system informacji o pożarach FIRMS, podjęto się próby udokumentowania, iż uwzględnione źródła zanieczyszczeń miały pochodzenie naturalne, a działalność człowieka w żaden sposób nie decydowała o emisji i jej wielkości.

Słowa kluczowe: *zanieczyszczenie pyłowe, modelowanie zanieczyszczeń powietrza, ocena jakości powietrza, monitoring środowiska, pożary lasów*