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Analysis of Air Pollution Migration during COVID-19 Lockdown in Krakow, Poland

Mateusz Zaręba*, Tomasz Danek

Department of Geoinformatics and Applied Computer Science, Faculty of Geology, Geophysics
and Environmental Protection, AGH University of Science and Technology, 30-059 Krakow,
Poland

ABSTRACT

The historical analysis of particulate matter (PM) concentration proved that pro-clean-air legislation and grassroots movement have a positive impact on air quality in Krakow. However, when the temperature drops in late autumn, winter, and early spring, the problem of smog still occurs in the city. In a 24-hours averaging period, the concentration of PM₁₀ has exceeded EU norms in 10 days in pandemic March 2021. It is estimated that 50% of the carbon fraction in PM₁₀ measured in Krakow comes from domestic heating. This is mostly caused by the migration of air pollutants from neighboring municipalities (where the use of fossil fuels for heating is allowed) to Krakow (where this type of households heating is forbidden). In this paper, we analyzed PM₁₀ concentrations in Krakow and neighboring municipalities. Moreover, we showed the main migration directions of air pollutants in connection with wind direction. We used statistical analysis to examine the relations between PM₁₀ concentrations and other physical characteristics of the atmosphere. It includes measurements of pressure, temperature, and humidity. We were collecting data during early spring 2021 when car transportation was limited due to the COVID-19 lockdown in Poland. Car transportation in Krakow is responsible for up to 20% of the PM₁₀ carbon fraction concentration. It allowed for observation of air pollutions from solid fuel heating with minimum traffic-generated pollution background. The Airly© low-cost sensors (LCS) network was used for this study.

Keywords: Air quality monitoring, LCS, Air pollution measurements, Particulate matter, Fossil fuels heating

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* **Corresponding Author:**

Zareba@agh.edu.pl

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1 INTRODUCTION

The problem of air pollution in Krakow has a long history. In the 1970s and 1980s, industry, mainly metallurgy, was one of the main air pollution factors. Over the years, as the population increased, the role of this factor decreased in favor of low emissions from fossil fuels heating and transportation (Bokwa, 2007). Krakow city's geographical location is well described in the literature (Morawska-Horawska and Lewik, 2003; Bokwa, 2019), as well as its geological structure (Rutkowski, 1989). The city itself cannot be considered in an isolation from the mesoscale landform features of the region. The general geographic information and urbanization relationships are described in the official Malopolska region strategy document (Urbanowicz *et al.*, 2020) while the information about the near-surface geological structure has been the subject of many studies (Foldvary, 1998; Zaręba *et al.*, 2020). Krakow is located in the valley. From the north, the elevation gain is related to Polish Jurassic Highland, on the south with limestone outcrops and Wielickie foothills. In a more mesoscale approach, going further south, there is the Carpathian inner-mountain basin and the Carpathian Mountains are just 100 km away (Gradziński, 1972). On the west Krakow borders with fault-block hills of Krakow Gate and Oswiecim basin, and from the west with Sandomierz lowland basin. The main river flowing through the city from west to east is the Vistula River (Hrehorowicz-Gaber, 2015). The latest research shows that thanks to pro-clean-air legislation,

the average PMs concentration in the city of Krakow has been systematically decreasing since 2011. Reduced car traffic during the COVID-19 pandemic allowed us to observe the influx of pollutants from fossil fuels heating to the city of Krakow from nearby towns. The Municipal Traffic Engineer Department research clearly shows that at the biggest city intersection during the COVID-19 pandemic period were on average 40% fewer cars compared to the pre-pandemic year 2019 (The Municipal Traffic Engineer Department, 2020). According to the Central Statistical Office of Poland's official data, every fifth inhabitant of large provincial cities (including Krakow) changed their work to remote work during the pandemic in 2021 (Statistics Poland, 2021b). The most remote work was performed by employees of the following industries: IT and communication (57%), financial and insurance (30%), employees of universities (30%) (European Commission, 2021). Krakow's universities conducted remote learning throughout the entire period of the pandemic (Kołodziej, 2021). The period of the pandemic in Poland can be divided into several stages, which are characterized by a total lockdown, a partial lockdown (with elements of sanitary restrictions easing), and periods without sanitary obstacles. The first case of coronavirus in Poland was diagnosed on 4th March 2020 (Raciborski *et al.*, 2020). The most severe lockdown was the first one introduced on 24th March 2020, in which domestic movements for people in Poland were prohibited, except for commuting to the necessary workplaces, grocery shops, hospitals, and pharmacies. The prohibition of access to forests, beaches, or parks was announced as well (Szumowski, 2020). Limiting the restrictions was divided into 4 stages (Serwis Rzeczypospolitej Polskiej, 2020). In the fall, restrictions resumed, but the lockdown was less severe than that announced in March. Until 25th March 2021, full-time education in special schools and the first grades of primary school was allowed. In the other cases, there was a requirement for remote learning. Gyms, sports clubs, spas, cinemas were closed and shopping malls were partially open with a significant reduction in the number of visitors. The restaurants served take-out only. There was a strict obligation to observe the sanitary regime and social distance (Morawiecki, 2021a). As of 25th March 2021, the lockdown rules were tightened. All educational institutions, nurseries, shopping malls, and hotels have been closed (Morawiecki, 2021b). On 19th April 2021, the lockdown ended and the restrictions were gradually loosened (Serwis Rzeczypospolitej Polskiej, 2021).

Many studies show that overexposure to PMs may be the main factor in the development of many disease entities. This includes problems with the respiratory and circulatory systems (Dai *et al.*, 2014), the occurrence of certain types of cancer (Raaschou-Nielsen *et al.*, 2013), and even problems with procreation (Pedersen *et al.*, 2013). Apart from the diseases presented above, the influence of PMs on the development of neurological diseases cannot be omitted. Relatively new research in this area shows the impact of PMs pollution on the development of diseases such as Alzheimer's or Parkinson's (Thurston *et al.*, 2017). Bokwa (2008) showed that long-term exposure to air pollution has a very negative impact on the health problems of Krakow habitants. There are also similar conclusions from a recent study done by Traczyk and Gruszecka-Kosowska (2020).

In Poland, air pollution monitoring is carried out under European Union directives and law. The main document on which the current air pollution law is based is directive 2008/50/EC (in law 21 May 2008). This directive uses the acronym AAQD - Ambient Air Quality and cleaner air for Europe Directive (European Parliament, 2008). There are over 4300 air pollution reference monitoring stations (PM₁₀ and PM_{2.5}) in the EU, including 288 in Poland. Krakow city is located in zone PL1201 with only a few measurement stations of PM₁₀ and PM_{2.5} – three automatic for both PM₁₀ and PM_{2.5}, two manual for PM₁₀, and only one manual measurement for PM_{2.5}. Based on the EU legislation, the Polish legislator introduced the standards for PMs concentration (25 µg m⁻³ for 1-year averaging for PM_{2.5}, 50 µg m⁻³ for 24-hour averaging for PM₁₀) and their measurements as well. For gravimetric manual measurements it is norm PN-EN 12341, and for automatic measurements norm PN-EN 16450 (Chief Inspectorate for Environmental Protection, 2021).

Reference stations allow for very detailed measurements with high accuracy, however, their rare number is not enough for geospatial analysis or pattern investigation. For this purpose, low-cost sensors (LCS) can be used, however, currently, the EU does not allow measurements from these sensors for reporting. The reason is that measurements from LCS can be affected by many different factors – mostly weather-related like humidity. On the other hand, the EU stands that in many cases, LCS gives comparable results with reference stations (Gerboles *et al.*, 2017). There are a few groups of LCS based on physical and chemical characterization. The most popular sensors in Krakow are Airly optical sensors (<https://map.airly.org/>). The use of local geospatial

analysis methods and dedicated solutions allows for a much better understanding of many phenomena (Briggs *et al.*, 2010; Hysenaj, 2016; Zaręba *et al.*, 2019; Lupa *et al.*, 2020). Based on previous research, Airly LCS accuracy in this period was very similar to the reference station measurements and this allows them to be used for geospatial analysis. It is important to know that LCS sensors need to be corrected according to the reference station measurements and weather-related conditions to provide reliable measurements of PM concentrations. On the other hand, the uncertainties of their measurements are greater than those of traditional measurements at reference stations, and their determination is more complicated (Peltier *et al.*, 2021). Each Airly sensor is dynamically calibrated using factors generated by artificial intelligence (AI) and machine learning (ML) algorithms based on the specific characteristics of the particular location. Data that are available through their API for public use are already corrected according to the factors mentioned before. Airly is not sharing its calibration algorithms with the public (Airly, 2021b). However, the use of ML techniques for this purpose is well established and has been published in many papers (Zimmerman *et al.*, 2018; Okafor *et al.*, 2020; Wang *et al.*, 2020), as well as discussed in the official World Health Organisation and World Meteorological Organization report (Peltier *et al.*, 2021). It was also shown that during the COVID-19 pandemic spring the migration of air pollutions from solid fuels heating from surrounding municipalities to Krakow was the main source of PMs in the city as transportation was significantly reduced due to lockdown. Research made by scientists from AGH, commissioned by Krakowski Holding Komunalny (KHK) SA in Krakow, with the substantive support of the Voivodeship Inspectorate for Environmental Protection (WIOŚ) and the Chief Inspectorate for Environmental Protection (GIOŚ) and the financial participation of the Air Quality Department of the Municipal Office of Krakow and companies from the Miejskie Przedsiębiorstwo Energetyki Ciepłej SA and Miejskie Przedsiębiorstwo Komunikacyjne SA, showed that almost 50% of PM₁₀ consist of carbon fraction, 20% are inorganic secondary aerosols, the remaining ions are about 10%, 3–4% are metals, and the rest are unidentified components. Detailed studies of the isotopic composition of carbon proved that a major part of that fraction is coal. Its share and sources turned out to be varied due to the period of the year – from solid fuel heating – during autumn-winter-early spring period it is about 50%, while in the rest of the year it is about 20%. The share of transport traffic varied depending on the location and year period. During summer it was 32–42%, while during winter it was about 11–22%. The biogenic fraction part of carbon (natural emissions and biomass combustion) remains constant at around 30% (Voivodeship Sanitary Inspectorate, 2020). Report of the National Center for Emission Management and Balancing, Institute of Environmental Protection - National Research Institute shows that 50% of emission sources of PM₁₀ and PM_{2.5} in Krakow are related to non-industry solid fuel heating, 9% of sources are manufacturing processes, 10% are related with industry combustion process while agriculture is the source of only 4.6% of PM₁₀ pollution (Institute of Environmental Protection – National Research Institute, 2019). In our previous study including observations from the last 10 years, we showed also that pro-clean-air legislation in Krakow and grassroots movements helped to decrease average PM concentration in the city prohibiting the use of solid fuels heating. We also demonstrated the relation between relative comfort zone temperature (Jendritzky *et al.*, 2001) and the level of PM₁₀ concentration from solid fuel heating in neighboring municipalities. We have shown that the feeling of cold determined based on the temperature measured by particular sensors at a given hour is a factor that allows identifying sources of pollution from solid fuels heating. For this purpose, we used spatial-temporal analysis of temperature and PMs concentration together with kernel density estimate of PMs and temperature concerning Predicted Mean Vote (PMV) and Perceived Temperature (PT) indicators (Jendritzky *et al.*, 2001). We have indicated the places that were the main sources of air pollution transported to Krakow by diffusion during the spring lockdown in Poland (Danek and Zaręba, 2021).

In this study, our goal was to investigate the main sources of PMs pollution in accordance with wind direction and geographical location using a dense grid of Airly LCS. We wanted to examine the impact of particular towns and villages surrounding the city of Krakow not in a general way but with the use of categorization. According to Statistics Poland, Krakow has over 700,000 inhabitants while the number in the whole Krakow agglomeration (Krakow and surrounding municipalities) is close to 1.5 million (Statistics Poland, 2021a). Our goal was also to check whether there is not only spatial but also temporary evidence that pollutants emitted in neighboring municipalities are finally transmitted to the city of Krakow. The presented paper shows the unique use of a

dense LCS grid for pollution migration during the COVID-19 pandemic period in a very specific region of Europe. Despite the very restricted air protection law, Krakow is still one of the most polluted cities in the world (Rogala, 2021).

2 METHODS

The experiments were conducted using a quasi-regular, dense grid of 90 Airly optical LCS (data available from: <https://map.airly.org/>, accessed on 28 September 2021). The free license of Airly allows for the use of no more than 100 sensors through their API. Sensors provided measurements of PM_{10} , $PM_{2.5}$, and PM_1 concentration, pressure, temperature, and humidity. Based on correlation analysis between PM_1 , $PM_{2.5}$, and PM_{10} (see Table 1) we decided to use in this study only PM_{10} measurements as a good representative of air pollutions from solid fuel heating with a correlation coefficient with $PM_{2.5}$ equals 0.997 and with PM_1 equals 0.996. The comparison was made based on Airly LCS averaged measurements in March. There are also other motives for which the PM_{10} fraction was selected for further analysis. EU standards for PM_{10} concentration are significantly higher than for $PM_{2.5}$, thus it is better to choose PM_{10} while considering LCS as the accuracy for PM_{10} measurement is about 20% of EU norm, while for $PM_{2.5}$ it is 50%. Another thing is that many reports and research done in the past were conducted on PM_{10} concentration or PM_{10} fraction analysis. It is also important that the PM_{10} fraction contains information on all particles smaller than 10 microns including particles smaller than 2 microns. In light of these facts, it is reasonable to choose the PM_{10} as a representative for further analysis. Because Airly sensors can be used by everyone who wants to buy them, the physical coverage of sensors' location in Krakow and neighboring cities is not regular. To provide the quasi-regular grid the custom algorithm in R was written. The k-nearest-neighbors method was used to find the sensors closest to the 100 point grid (in X and Y directions) and then the criterion of the quarter of the distance between particular sensors and grid points was used to decide if the sensors should be included or excluded. Data were collected hourly between 3rd March 2021 and 16th April 2021. The legibility of the PM measurements was proved by the time-series analysis of the government station and the Airly LCS (Danek and Zaręba, 2021). Manufacturer guarantee accuracy of Airly sensors for – PM_1 $5 \mu g m^{-3}$ in the range $0-100 \mu g m^{-3}$ and $10 \mu g m^{-3}$ over $100 \mu g m^{-3}$; for $PM_{2.5}$ $10 \mu g m^{-3}$ in the range $0-100 \mu g m^{-3}$, 10% for measurements in the range $101-500 \mu g m^{-3}$, and 20% over concentration $500 \mu g m^{-3}$; for PM_{10} accuracy is the same as for $PM_{2.5}$ (Airly, 2021a). Sensor 36808 located in Niepołomice is the nearest to an official government PM_{10} station located on 3 May Street in Niepołomice. Airly sensor 36808 measurements were averaged in a 24-hour window and plotted together with the government sensor measurements (see Fig. 1). The correlation coefficient between their measurements in the presented period was high – over 0.93 (Danek and Zaręba, 2021).

This period was chosen as it was the last strict lockdown in Poland. More or less strict lockdown regulations were in force from 8th August 2020 to 24th May 2021 with various changes during this period depending on the number of COVID-19 cases. Due to the rapid increase in infections numbers since the beginning of March, from 25th March 2021 to 19th April 2021, the lockdown was tightened (see in detail in the introduction). Krakow's labor market is dominated by employment in the IT, financial services, and education sectors (European Commission, 2021). It is known from the Central Statistical Office of Poland that most of these workers during the pandemic performed their work remotely without having to travel to their place of work (Statistics Poland, 2021b). Moreover, the number of students is almost 20% of the inhabitants of Krakow (Dębkowska *et al.*, 2019). In the analyzed period, all of the mentioned above groups worked or learned remotely without generating car traffic. According to the official statement of

Table 1. Correlation coefficients for the PMs values obtained from Airly LCS sensors for the investigated period in March for all data points.

Concentration ($\mu g m^{-3}$)	$PM_{2.5}$	PM_1	PM_{10}
$PM_{2.5}$	1.000	0.998	0.997
PM_1	0.998	1.000	0.996
PM_{10}	0.997	0.996	1.000

Fig. 1. LCS Airly sensor 36808 (mint) validation according to twenty-four-hour averaged measurements of PM₁₀ from government stations (brown) (Danek and Zareba, 2021 modified).

the General Directorate for National Roads and Motorways, the average number of cars per day across the country decreased by 2,166 vehicles per day in March 2021 compared to March 2019 which is about a 10% total reduction due to pandemic lockdown (General Directorate for National Roads and Motorways, 2021). In Krakow, the reduction in car traffic was about 40% (City Traffic Engineer of Krakow, 2020). Additionally, to minimize the impact of car traffic on the analysis of PMs concentration, the hours with the lowest car traffic were selected. Measurements of the traffic volume at the inlets to the city of Krakow, with particular emphasis on transit traffic done by Krakow city, showed that car traffic between hour 10 PM and 6 AM is minimal, while traffic is the greatest between 6 AM–9 AM and 1 PM–6.30 PM (Rosiek, 2017). The main sources of PM pollution in Krakow are low emissions from heating and car traffic (Traczyk, 2020). Selecting the lockdown period and hours in which, under non-pandemic standard conditions, the car traffic drops to almost zero, it made possible to observe pollutants from solid fuels heating only.

To choose days for directional air pollution inflow study the detailed analysis of PM maps was done (created in R using Thin-plane spline (TPS) interpolation method by Nychka *et al.* (2021)).

According to the WMO report (Peltier *et al.*, 2021), the uncertainties of LCS measurements are higher than those for reference stations. According to the standard, the precision for gravimetric measurements is $2 \mu\text{g m}^{-3}$ (European Parliament, 2008), while for Airly sensors, the manufacturer declares it at the level of $10 \mu\text{g m}^{-3}$ for PM₁₀. So it is five times lower. LCSs are sensitive to the influence of atmospheric factors, however, the data provided by Airly is already corrected, and the total uncertainty of individual sensors is not shared. The correlations of indications to the closest reference stations prove the high accuracy of the measurements (Fig. 1). In accordance with the LCS data processing standards specified in the WMO document (Peltier *et al.*, 2021) for Level-4 (Schneider *et al.*, 2019), we made continuous spatial distributions using the TPS method and analyzed the differences between these distributions and the indications of individual sensors. When analyzing a series of maps based on relatively sparse sensors network TPS has two important advantages over kriging. Firstly it does not require semi-variogram fitting thus different maps are directly comparable without any spatial model assumptions. Secondly, the TPS method is very resistant to separated anomalous sensor readings that can occur in sparse networks of LCS due to both measurement errors or the very local character of the observed phenomenon. This effect can be seen in the first map of Fig. 10 (2021-03-15 19:00) in Section 3.3.1 where four extremely high values were observed. The maximum residual value was equal to 184 mg m^{-3} (Table 2). But as for all these four sensors, the values from neighboring sensors were much lower the anomalies are not observed in the final map. Of course, these separated readings may represent the beginning of pollution emission but their point character makes them impossible for spatial interpretation. Please note that on the other maps such extremes have not been observed (Table 2). It is also worth noting, that increased residuals were observed only in the period when the onset of emission occurs (15-03 19:00 and 16-03 01:00) and not when the maximum pollution levels were recorded. It may indicate that these were not sensor errors but real point observations that have not yet propagated to neighboring sensors. The comprehensive distribution evaluation of PM together with humidity, temperature, and pressure were also performed to study other than wind and geomorphological conditions of PM migration. We used charts and cross-plots taking into account the differentiation by European Air Quality Index.

Table 2. Summary statistics for estimation errors in sensors network for TPS map models used for geospatial analysis.

Map	PM ₁₀ concentration ($\mu\text{g m}^{-3}$)				
	Min	1 st quartile	Median	3 rd quartile	Max
15 th March 19:00	-54.17	-23.67	-10.99	5.98	182.43
16 th March 01:00	-41.41	-15.04	-1.59	11.23	50.09
16 th March 02:00	-2.50	-0.68	-0.18	0.70	3.02
16 th March 06:00	-12.52	-1.97	-0.20	1.75	13.42
18 th March 02:00	-9.89	-1.95	-0.47	1.24	22.40
18 th March 03:00	-12.01	-1.95	-0.31	1.74	17.86
18 th March 04:00	-11.17	-2.84	0.08	1.84	16.19
18 th March 05:00	-11.71	-3.00	-0.08	2.54	11.65

The lag analysis was performed to study if the time dependency exists between higher emissions of PM in neighboring municipalities and Krakow city. First, the collected dataset was split into data from sensors outside and inside Krakow. Secondly, the sensors outside Krakow were split into groups depending on the main wind direction on a particular day. This allows for the examination of two-time series using the cross-correlation method. This makes it possible to objectively examine if there is a match between the distributions (between sensors group outside and inside the Krakow) and also to see the time difference. During the examined period the main wind direction was west. Only a few days have a dominant north wind direction. There were also days with the very weak wind where the direction was changing from hour to hour. These were classified as no wind days. For the group of sensors outside the Krakow city the following LCS were chosen: group for west wind: 33051 located in Liszki, 8082 Jeziorzany, 37009 Rzozów, 36808 Skawina, 11672 Czernichów, 6163 Stanisław Dolny, 18706 Brzeznicza, 11660 Rybna; group for north wind: 31100 Biały Kościół, 492 Brzozówka, 38553 Gotkowice, 313 Skala, 32908 Tomaszowice, 2655 Więckowice (see map in Fig. 2).

Fig. 2. Krakow and neighboring municipalities map with localization of sensors in west and north group (map sources: ESRI and Stamen).

3 RESULTS AND DISCUSSION

3.1 Pre-pandemic and Pandemic PM Concentration Analysis

Without a doubt, the COVID-19 pandemic changed the way we live. Restrictions altered our habits, the way we work, study, and travel. To examine its effect on general PM_{10} concentration the 24-hour measurement from the official government mass station on Bujaka street in Krakow, from the last 4-years was plotted (see Fig. 3). It can be noticed that in general, the concentration of PM_{10} in Krakow is decreasing year to year. It is related to law changes and grassroots movements that are present in Krakow since 2011 (Daneke and Zareba, 2021). Fig. 4 shows the

Fig. 3. 24-hour averaged PM_{10} concentration in Krakow for years 2018–2021. Measurements from reference station located on Bujaka street in Krakow. (Data source: Chief Inspectorate for Environmental Protection, 2021)

Fig. 4. Average PM_{10} concentration and temperature in March 2018–2021 (Data source: Chief Inspectorate for Environmental Protection, 2021 and Institute of Meteorology and Water Management - National Research Institute, 2021)

temperature in March from the year 2018 to 2021, together with the average PM_{10} concentration. The main factor for PM_{10} concentration in this month is the temperature. As mentioned before, the main source (over 50%) of PM_{10} pollution in Krakow is solid fuel heating, so naturally, the temperature will have a dominant impact on its concentration. However, in this study, we wanted to examine the effect of PM_{10} migration from solid fuel heating without additional background noise from car transportation (source of 11–22% depending on localization in the pre-pandemic year) which were limited during the lockdown. Summing up, the impact of the pandemic on the overall concentration of PM_{10} in the atmosphere in Krakow is not dominant, however, it is crucial to eliminate the influence of the car transportation background. When analyzing the values in individual years in March, it is not possible to conclude unequivocally about the impact of the lockdown itself, as it is clearly visible that the dominant factor is temperature, which results directly from the specificity of heating houses in the region.

3.2 Relation between PM Concentration and Other Physical Atmosphere Parameters

Fig. 5 shows a graph for PM_{10} , temperature, humidity, and pressure measurements for all 90 sensors in the whole investigation period. Fig. 6 demonstrates the relation between PM_{10} concentration and other physical measurements in the context of the European Air Quality Index. Figs. 6(a) and 6(d) show the relation between temperature and humidity for Krakow city and neighboring municipalities. The relation between pressure and temperature is shown in Fig. 6(b) (Krakow city) and Fig. 6(e) (neighboring municipalities). Finally, the pressure and -humidity relation is demonstrated in Fig. 6(c) (Krakow city) and Fig. 6(f) (neighboring municipalities). The analysis of individual weather factors for PM_{10} indications is extremely difficult. According to the Czernecki *et al.* (2017) study, the key factor is wind.

It is clearly visible that a higher concentration of PM_{10} is strongly related to pressure. When the pressure was below 1005 hPa in the examined spring period, the air quality was good and no matter what the temperature values were. A similar situation is for humidity, only for neighboring municipalities some measurements gave a slightly worse index of air quality for humidity over 60% for pressure below 1005 hPa. The worst air quality index is for pressure range 1005 and 1015 hPa, but it changes in the range 1015–1020 hPa where the strong temperature dependence is visible (when dropping below comfort zone (Jendritzky *et al.*, 2001)). We can conclude that the highest concentration of PM_{10} is related to high pressure, low temperature, and high humidity, but with the dominant role of pressure (compare Ning *et al.* (2018)). These observations are in the line with Wilgoński and Czerwińska's (2020) study about smog episodes in Poland. They proved that during the cold season high pressure is related to anticyclone circulation of very dry and cold air masses. During the night temperature drops significantly and during the day temperature increase. This situation leads to temperature inversion between cooler ground and warmer atmosphere. When the humidity is relatively low and the temperature is high, the PM_{10} quality index is good. However, this relation can be distracted by high pressure. This effect can be observed in Fig. 5 - on 29th March, where is a relatively high temperature, low humidity, and high pressure and a noticeable higher concentration of PM_{10} compared to the previous day where

Fig. 5. The pressure (green), humidity (orange), temperature (red), and PM_{10} (black) in the investigated region from Airly LCS measurements.

Fig. 6. Cross-plots for physical atmosphere parameters measured in sensors during spring divided into groups according to European Air Quality Factor – (a) relation between humidity and (d) temperature in Krakow and neighboring municipalities; (b) the relation between pressure and temperature in Krakow and (e) neighboring municipalities; (c) the relation between pressure and humidity in Krakow and (f) neighboring municipalities.

pressure was much lower. According to Zhang *et al.* (2017) study, the effect of the humidity on PM concentration while atmospheric conditions are stable is low, however, relative humidity fluctuations can have a strong impact on pollutions concentration.

To aggregate information from the regions of interest, namely west, north and Krakow groups we calculated daily averages and standard deviations of all available PM₁₀ readings from LCS stations in a particular group (see Fig. 7) and averages of meteorological factors (see Fig. 8). Results obtained for temperature, humidity, and pressure are nearly identical in all groups whereas PM₁₀ averages differ substantially. As expected readings from Krakow city are more similar to readings from the west group. This effect is cost by the dominant west wind direction. In general, values obtained for Krakow city are lower than those obtained for the west group, but in the days when the west wind is relatively stable and not too strong (e.g., March 16th) difference between these values disappears. Daily average uncertainties of PM₁₀ concentration measurements for Krakow and the north group are lower than those obtained for the west group. It may suggest more local character of emission in this group.

3.3 Analysis of Air Pollution Inflow Concerning Main Wind Direction

It has been shown that the migration of PM from neighboring municipalities to Krakow city, on days with no wind takes place by gravity fall or by diffusion as the city is located in the valley (Danek and Zaręba, 2021). Our goal was to check how the migration process of air pollutions depends on an additional external factor like the wind. During the studied period, the dominant wind direction was west (see Fig. 9). In the examined period the highest wind speed is related to wind direction SW. The south direction can be associated with a strong Föhn wind type which, under favorable conditions, may even have an impact on the regions of central Poland. This is a kind of warm and dry wind associated with the downwind slope of the mountain range (Marcinek *et al.*, 2016). There were a few days with dominant north wind direction. For example, the good conditions for observation the inflow of PM₁₀ to Krakow was the night between 15th and 16th March. In Fig. 5 it is clearly visible that those days are a part of days in the period when the increasing trend of pressure and decreasing trend of temperature with relatively high, stable

Fig. 7. Daily averaged PM₁₀ Airly LCS measurements in the three groups: west (red), north (blue), and Krakow city (green).

Fig. 8. Daily averaged meteorological factors for the three groups: west (red), north (blue), and Krakow city (green).

Fig. 9. Wind direction (orange) and wind speed (blue) for Krakow-Balice meteorological station (data source: Institute of Meteorology and Water Management - National Research Institute, 2021).

humidity are present. Furthermore, the temperature at the night is lower than in the next two days, even if the general 24-hour temperature is decreasing. The temperature on this night drop below comfort zone temperature and it is the main factor of increased heating of the households and therefore the main factor for generating air pollution as well.

3.3.1 The inflow of pollution when the dominant wind direction is west

Fig. 10 presents maps of PM_{10} inflow to Krakow city on the night between 15th and 16th March in hours: 19:00 15th March; 01:00 16th March; 02:00 16th March; 06:00 16th March. This is the time when car traffic in Krakow is close to zero. Additionally, the lockdown is a factor reducing population mobility resulting in reduced possible migration of pollutants generated by car traffic at other times of the day. As in Krakow and neighboring municipalities, two main PM sources are related to heating and transportation, we can conclude that the observed pollution is generated by solid fuels heating in neighboring municipalities. It is clearly visible that in the evening there is generally

Fig. 10. Maps of PM₁₀ inflow with west dominant wind direction in the night between 15th and 16th March. White arrows indicate wind direction. Asterisks represent sensors' localizations, the blue line represents the Vistula River, red circles represent sensors with high residual value.

an increased level of PM₁₀ concentration in neighboring municipalities while the air in Krakow city beside Nowa Huta region is pretty good. After midnight, when the temperature dropped significantly the higher concentrations of PM₁₀ are visible in western regions. Wind speed is around 2 km h⁻¹. Fig. 11 shows the wind-rose diagram for the Krakow-Balice airport station (located on the northwest side of the investigated area) (calculated using <https://mesonet.agron.iastate.edu/>). In the next hour, the pollutants are transported to the city center through the Vistula River valley, to finally fill the city in a latitudinal arrangement around 6:00 16th March. The distribution of isolines is latitudinal with the highest concentration of PM₁₀ along with the river line and the lowest to the south and north of this line. The local depression along the river valley, the higher humidity in this area, and the tendency to form mists create a favorable environment for trapping transported pollutants in this area. Fig. 12 shows a backward trajectory for 10 hours on that day for 3 different locations in Krakow agglomeration. The trajectories were calculated using *READY* (Real-time Environmental Applications and Display sYstem) provided by National Oceanic and Atmospheric Administration (Rolph *et al.*, 2017). It is clearly visible that possible pollutant comes from the north and west surrounding of Krakow.

Fig. 11. The wind rose for Krakow-Balice airport meteorological station on March 15th and March 16th for time bounds 17:30–05:30. (Iowa Environmental Mesonet, 2021)

Fig. 12. Map of backward trajectory with ending time 19:00 on March 15th according to NOAA HYSPLIT model. (Map source OpenStreetMap and Leaflet, 2021)

Fig. 13. Averaged PM_{10} concentration in Krakow (blue) and a west group of sensors outside the city (red) from 14th to 19th March 2021.

Fig. 14. The autocorrelation function of averaged PM_{10} concentration series for west sensor group and Krakow sensors from 14th to 19th March 2021. The Blue dashed line represents statistical significance, the orange line represents maximum lag.

Fig. 13 shows two-time series – the blue line represents averaged PM_{10} values in Krakow city, and the red line shows averaged PM_{10} values for the west sensors group outside the city. The effect of locally highest emission on March 16th is clearly visible for both areas. Average values of PM_{10} concentration in the previous two days, and the following two days are noticeably lower. As mentioned before, mostly due to the minimal temperature value in the night between 15th and 16th March, which dropped around 0° Celsius. The lag between the maximum pollution point for west group sensors and the sensors in Krakow is visible. Fig. 14 shows the calculated lag value for those two time series for the same period as on the graph in Fig. 13. In general, the distribution for sensors in Krakow city is lagged about 1 hour compared to sensors in the west group.

3.3.2 The inflow of pollution when the dominant wind direction is north

Fig. 15 presents maps of PM_{10} inflow to Krakow city on the night and early morning on 18th March in hours: 02:00, 03:00, 04:00, 05:00. Again we choose hours when the car traffic is very low and when the effect of households heating can be observed as the temperature is below the

Fig. 15. Maps of PM₁₀ inflow with north dominant wind direction in the night and early morning on 18th March. Black arrows indicate wind direction. Asterisks represent sensors' localizations, the blue line represents the Vistula River.

comfort zone (Jendritzky *et al.*, 2001). We can say with certainty that the impact of PM sources other than those coming from heating is negligible at these times, especially during the period of partial lockdown with a relatively cold night. On that day around 02:00, Krakow and neighboring municipalities' air was very good. The situation started to change about 3:00 when the higher concentration of PM₁₀ began to form in the northern area of investigated region. The dominant wind direction on that day was north and north-north-west. Fig. 16 shows the wind-rose diagram on 18th March - again for the Krakow-Balice airport station. In the next hour the pollutions were transferred into the north region of Krakow city – to the Bronowice, Prądnik Biały, Prądnik Czerwony and Krowdrza. In the next hour, the pollutions were in the whole city and also in Wieliczka and other cities in the south of Krakow. For the rest of this day, there was no wind and the temperature was around 6–8 Celsius degrees. Later in the evening on this day, the effect of diffusion and gravity fall of pollutants into the city was shown by Danek and Zaręba (2021). Fig. 17 shows a backward trajectory for 10 hours on that day for 3 different locations in Krakow. The trajectories were again calculated using *READY*. It is clearly visible that pollutants entered Krakow from the north.

Fig. 16. The wind rose for Krakow-Balice airport meteorological station on March 18th for time bounds 02:30–04:30 (Iowa Environmental Mesonet, 2021).

Fig. 17. Map of backward trajectory with ending time 02:00 on March 18th according to NOAA HYSPLIT model. (Map source OpenStreetMap and Leaflet, 2021)

Fig. 18 shows two-time series – similar to those in Fig. 13. Blue line again represents averaged PM_{10} values in Krakow city but the red line shows averaged PM_{10} values for the north sensors group outside the city. The situation is slightly different than presented in the example before. Here there are the following days on steadily decreasing temperature trend with a clear uptrend for pressure. We can observe continuous lag between sensors outside and inside Krakow. Of course, the lag for the maximum pick on 18th March 01:00 for the north sensors group and sensors in Krakow is mostly dominated by the wind. The pollutants are transported to Krakow, but on the other hand in presence of north wind, they are quickly blown out from the city to the south. In the next days presented on this graph, the wind speed is very low, close to zero, so the higher concentration of PM_{10} transported into the city remains there longer as the city is located in the valley. Fig. 19 shows also the 2 hours lag between distribution for the north group of sensors and sensors in Krakow. It seems that the terrain causes that pollution flowing in from the north takes longer to enter the city than when it enters the Vistula valley from the west. It is a valuable observation in the case of the future forecasting of the pollution level in Krakow city.

Fig. 18. Averaged PM_{10} concentration in Krakow (blue) and a north group of sensors outside the city (red) from 17th to 22nd March 2021.

Fig. 19. The autocorrelation function of averaged PM_{10} concentration series for north sensor group and Krakow sensors from 17th to 22nd March 2021. The Blue dashed line represents statistical significance, the orange line represents maximum lag.

4 CONCLUSIONS

The conducted research clearly shows that pollutants generated in neighboring towns are transported with the wind to Krakow city. With a specific system of pressure, temperature and humidity, they can remain in the city to which they were transported for a long time. This situation can be even worst during the cold season when the Polish-type smog occurs (Wielgosiński and Czerwińska, 2020) Due to the partial lockdown introduced by the Polish government the PM concentration noise from transportation was limited and observation of the almost clear effect from solid fuels heating was possible. In addition, the analyses were carried out in temporal windows, in which car traffic was minimal. The temperature was also low enough and inhabitants of neighboring municipalities had to heat their houses. An important observation is that the west wind is conducive to the rapid transport of pollution to the city. Even if the wind speed is relatively low. Backward propagation study showed that pollutants emitted in the north can easily enter the city through the west air gate. The maximum PM₁₀ concentration with the domination of these winds coincides with the Vistula River valley. The Vistula valley runs through important and historical parts of the city with increased tourist traffic, which may make Krakow's visitors feel that the city is a smog generator itself, while Krakow has one of the most pro-clean-air legislation in Poland in force. The lag between increased pollution in neighboring cities on the west and pollution increase in Krakow is about 1 hour. In the case of days when the north wind is dominant, the lag is about 2 hours. It is related probably to a natural barrier of hills on the north side. What is more, in presence of north wind, the pollutions are transported out much faster than it was when west winds occurred.

Banning the use of solid fuels for heating in selective cities does not relieve these cities from the air pollution problem related to solid fuels. It is important to extend the ban on solid fuel use for heating in Krakow to other localities in the Krakow agglomeration. Firstly, because of the health of the inhabitants of these particular towns, but also for the health of the inhabitants of Krakow. The research cited in the introduction clearly shows the facts of a health problems occurrence associated with exposure to air pollution. Secondly, because of the tourist traffic. After the transformation period, Krakow has become one of the most visited cities in Europe (Kowalczyk-Anioł *et al.*, 2021), therefore taking care of the positive perception of the city, including clean air, is in the interest of the inhabitants of the region working in the tourism industry.

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