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COMPARISON OF HIGH PM10 CONCENTRATION BETWEEN ŁÓDŹ AND SMALLER MUNICIPALITIES OF CENTRAL POLAND IN 2012–2023 IN THE LIGHT OF METEOROLOGICAL CONDITIONS

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Abstract. Long-term human exposure to particulate matter with a size equal to or less than 10 micrometers may lead to serious health problems such as respiratory and cardiovascular diseases or cancer. Whereas in most of Europe the number of premature deaths decreased significantly over more than a decade, in Poland, it remained at the same level. In Central Poland, as in the rest of the country, the main reason for high PM10 concentrations is low-level emission from single-family houses, which are often poorly insulated and heated by old furnaces with low-quality fuels or substitutes (i.e., wastes). The high concentration of PM10 in winter is exaggerated by meteorological conditions that usually do not favour the dispersion of pollutants. High and very high PM10 concentrations occurred during anticyclonic weather, when high pressure, limited turbulence, subsidence of the air, low wind speed and lack of precipitation hindered air pollution removal. The highest probability of high PM10 concentration episodes is for the air mass inflow from the eastern (NE–E) and southern (SW–S) sectors when the anticyclone center is located in the north-east or south-east of Poland. Additionally, decreasing temperatures in winter increase the demand for heating and coal combustion. In Central Poland, from 2012 to 2023, the air quality significantly improved. Since 2019, the annual PM10 standards have been met at all stations, and the 24-hour limits are exceeded in only some of them. The most polluted urban areas in Central Poland are Opoczno, Radomsko, Zduńska Wola, Piotrków Trybunalski and Łódź, and the level of pollution is not related to the number of citizens. In many cases, considerably less-populated cities such as Opoczno, Zduńska Wola or Radomsko are more polluted than Łódź.

Key words: air pollution, Łódź voivodeship, Central Poland, meteorological conditions, PM10

Introduction

Particulate matter of 10 micrometers or less is harmful to human health due to its small size and high penetrability to the respiratory system. Long-term exposure to such particulate matter might lead to respiratory and cardiovascular diseases and cancer. According to the European Environmental Agency (EEA 2023), the air quality in Europe has improved following the zero pollution action plan (EC 2021), and the number of people dying due to fine particle pollution in the EU has nearly halved since 2005. Unfortunately, Poland is characterised by one of Europe's highest numbers (after Germany and Italy) of premature deaths attributed to exposure to PM2.5, at 46,300 deaths in 2018, with only a slight decrease of about 2,000 relative to 2013 and an increase of 4,000 relative to 2011 (Guerreiro *et al.* 2014, 2016; Ortiz *et al.* 2020). It was proven by Widziewicz *et al.* (2018) that, in Poland, the episodes of high concentration of carcinogenic compounds such as As, Cd, Ni, Pb and B(a)P have a much more significant negative health effect than in non-episodic time.

To protect human health, the European Parliament and the Council set a directive on ambient air quality and cleaner air for Europe (EU 2008). According to the Directive, the 24-hour PM10 limit is 50 μg/m^3, which can not be exceeded more than 35 times in a calendar year, and the annual limit (annual PM10 average) is 40 μg/m^3. The WHO recommendations since 2021 are far

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more restrictive, with a 24-hour PM10 limit of 45 μg/m^3, which can not be exceeded more than 3–4 times a year, and the annual limit is 15 μg/m^3 (WHO 2021).

Poland, next to Bulgaria, is the most polluted country in Europe in terms of PM2.5 concentration. Recently, thirty-six Polish cities have been ranked among Europe's fifty most polluted cities in previous years. Four of these cities are located in Central Poland (Loveair 2023). According to IQAir (2023), 12 of Europe's 100 most polluted cities in 2022 come from Poland, which might suggest that some improvement in air quality was made during the last few years. However, these statistics strictly relate to the year and calculation method. The PM10 limits were exceeded in 91% of the measurement zones of Poland – set out in Article 87[2] of the "Environmental Protection Act" (Journal of Laws 2024, item 54), with the air quality being worst in winter during the heating season in the southern and then central parts of the country (PwC 2018; Kowalska 2020; PAS 2023). In Poland, poor air quality mainly comes from burning low-quality fuels to heat houses, burning waste, fires in landfills, transport emissions, etc. (Wierzbińska, Kita 2024).

In Łódź voivodeship, hereinafter referred to as Central Poland, in 2022, most of the PM10 emissions come from residential areas (65.1%), then point emissions (energy sector, manufacturing, extracting industry, etc.; 7.2%), road transport (5.2%), slag heaps and excavation (5.7%) and other (agricultural, tractors, railways, agriculture, landfills, etc.; 17.4%) (GIOŚ 2023). In Europe in 2020, the residential, commercial and institutional sector was also the primary source of PM10, but it was only 44.0%, which is significantly less than in Poland (EEA 2020). In Poland, air-quality assessment is performed by zoning, and the result assigns a class to each zone for each of the assessed pollutants. The evaluation is performed considering criteria defined in terms of human health and plant protection. In 2022, the Łódź agglomeration zone and the whole voivodship zone were both ascribed C class due to exceeding the 24-hour PM10 standards and the target level of benzo(a)pyrene. The area of Central Poland (excluding Łódź agglomeration) additionally received class C1 due to exceeding the limit of PM2.5 concentration (phase II) (GIOŚ 2023). Assigning class C to a zone means that exceedances of acceptable or target levels plus a margin of tolerance, where this margin is defined, were found in its area.

The main issue of the paper was to characterise and compare the PM10 variability in selected urban areas of Central Poland from 2012 to 2023. The second goal was to answer questions such as whether the PM10 concentration is related to the number of citizens and what the role of meteorological conditions is on high PM10 concentration in most polluted urban areas. Only the manual stations were considered to obtain the most reliable datasets.

Study area, data and methods

Study area

Central Poland is mainly situatted in the lowland area, with slightly diversified relief between the Warsaw–Berlin Proglacial Stream Valley (<100 m a.s.l.) in the north and Łódź Hills (250––284 m a.s.l.) in the central parts. Łódź is the capital of the voivodship, with 655,279 citizens in 2023 (~28% of the voivodship population). In the last two decades, most of the voivodship, especially Łódź, have been depopulated. This was mainly due to the declining birth rate, demographic structure and migration changes. Additionally, in the case of Łódź (the largest city), strong migration to the city's outskirts was observed, and the population increase in the municipalities bordering Łódź, which is a natural process that characterises large cities. The economy of the region is mainly based on high-tech, electromechanical, energy, chemical, textile, metallurgical, food and building materials industries. It is also an important transportation hub. The most prominent power plant in the country is located south of Łódź and is based on the brown coal mined in Bełchatów and Szczerców. Due to the central location of the voivodship, numerous highways, expressways and national roads cross the region (Wachowiec *et al.* 2019).

Data and methods

In the study, the daily PM10 concentration data from 14 measurement stations in 2012–2023 were obtained from the Chief Inspectorate for Environmental Protection (GIOŚ 2024). In Central Poland, manual station filters are analysed for different pollutants based on their weight before and after sampling using the same weighing device. In the case of automated stations, the various sensors are mounted at other locations, and the correction factor has been changing over the years and was not always correctly adopted at some points. These led to over- or underestimation of PM10 concentrations. For higher data reliability, only the data from the manual stations were used, but their number in Central Poland is highly limited. The stations and their characteristics are listed in Table 1, according to population. These are the background stations, and most of them are surrounded by blocks of flats but, in individual cases, by tenement or single-family houses. Twelve out of 14 stations are urban stations, one is suburban (Uniejów), and the other one is extra-urban (Parzniewice). The completeness of datasets was from 95.7 to 99.9%, depending on the station. For the meteorological characteristics, the data from the Łódź-Lublinek and Sulejów stations were acquired from the Institute of Meteorology and Water Management, National Research Institute (IMWM-NRI 2023). The daily data of mean (T2m), maximum (Tmax), and minimum (Tmin) temperature, sea-level pressure (SLP), precipitation (RR) and hourly data on wind speed (WS) and direction (WD) were used from these two stations. All measuring environmental and meteorological stations are presented on the topography background in Figure 1.

The daily atmospheric circulation (the air-mass inflow direction and character) and vorticity were provided by Piotr Piotrowski from the Department of Meteorology and Climatology of the University of Łódź for the years 2012–2022. The atmospheric circulation was established based on an automatic method described by Jenkinson and Collison (1977). The number of grid points was increased to 32 (Piotrowski 2009), with the center grid set at 51.5°N and 19.25°E.

The mean value of hourly WS and WD data was also calculated and set as a daily wind speed and direction.

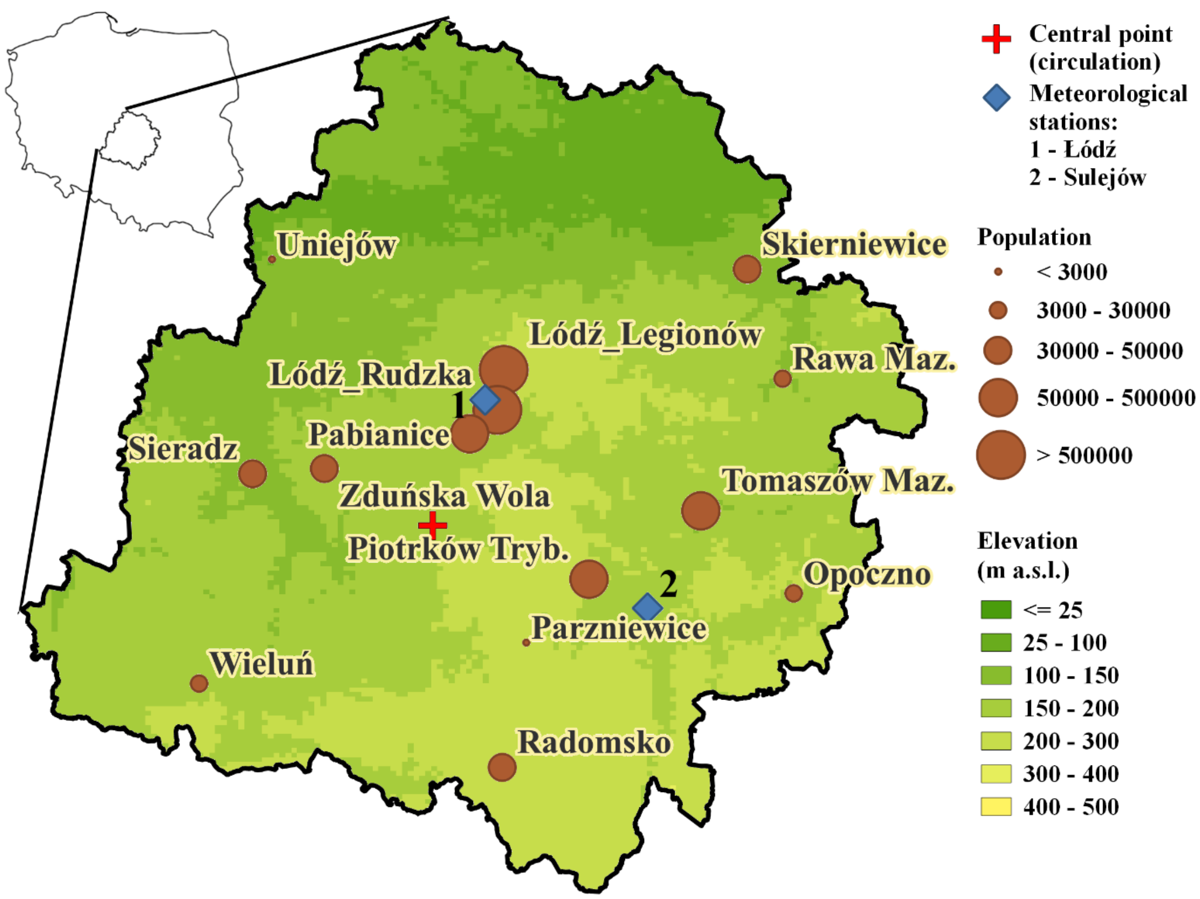

Fig. 1. Measurement station location on topographical background
Environmental stations are marked as brown dots, and meteorological stations are marked as blue diamonds.
Dot size refers to population size in municipalities

Table 1

Air-quality monitoring stations and their characteristics, according to population size in municipalities
Based on data obtained from GIOŚ (2023) and GUS (2023)

Station name	Coordinates	Data timeline	Station type	Area type	Population in municipalities	
					2012	2023
Łódź_Legionów	51° 46' 35.1012" N 19° 27' 10.5696" E	2012–2023	background	urban	718 960	655 279
Łódź_Rudzka	51° 42’ 20.0916” N 19° 26’ 5.4312” E	2012–2023	background	urban		
Piotrków Trybunalski	51° 24’ 15.8616” N 19° 41’ 49.0416” E	2012–2023	background	urban	76 400	66 901
Pabianice	51° 39’ 47.4516” N 19° 21’ 19.7496” E	2012–2023	background	urban	68 320	60 929
Tomaszów Mazowiecki	51° 31’ 34.5288” N 20° 1’ 0.4296” E	2012–2023	background	urban	65 450	57 728
Skierniewice	51° 57’ 15.5304” N 20° 8’ 57.7608” E	2012–2023	background	urban	48 700	45 403
Radomsko	51° 4’ 2.7804” N 19° 26’ 55.2984” E	2012–2023	background	urban	47 950	43216
Sieradz	51° 35’ 31.5996” N 18° 44’ 5.6328” E	2012–2023	background	urban	43 650	38 960
Zduńska Wola	51° 36’ 5.1804” N 18° 56’ 24.4392” E	2012–2023	background	urban	43 920	38 650
Wieluń	51° 13’ 4.1808” N 18° 34’ 54.5808” E	2013–2023	background	urban	23 840	20 682
Opoczno	51° 22’ 44.8608” N 20° 16’ 55.8084” E	2012–2023	background	urban	22 320	19 116
Rawa Mazowiecki	51° 45’ 39.15” N 20° 15’ 2.0484” E	2012–2023	background	urban	17 820	16 001
Uniejów	51° 58’ 17.9904” N 18° 47’ 25.26” E	2017–2023	background	suburban	3 020	2 954
Parzniewice	51° 17’ 28.23” N 19° 31’ 3.2016” E	2018–2023	background	rural	435	419 (in 2021)

Results

PM10 concentration variability in Central Poland

The annual PM10 concentration varied considerably among stations in Central Poland; nevertheless, in all cases, a significant decrease in their values has been observed since 2012 (Fig. 2A). In 2012–2015, the annual limit of 40 μg/m^3 was exceeded at most stations. Since 2017, at most stations (except Łódź_Legionów, Radomsko and Zduńska Wola), the PM10 pollution has decreased below the limit. Since 2019, the annual limit has not been exceeded at any station.

On a seasonal scale (Fig. 2B), the highest PM10 concentrations were noticed in winter (DJF). But at the same time, this season is characterised by the most significant PM10 decrease. In 2012, the winter mean concentration reached almost 80 μg/m^3, and in the last years, it decreased by more than half. Furthermore, during winter, the higher relation to minimum temperature is visible. The cold winters in 2012, 2017 and 2021 reflected relatively higher PM10 concentrations. On the other hand, the lowest recorded PM10 concentrations (32–33 μg/m^3) are related to the warm winters in 2020 and 2022–2023. In spring (MAM) and autumn (SON), the PM10 concentration decrease is much less pronounced but still visible (from about 42–46 μg/m^3 to 30 μg/m^3 or less). Nevertheless, there is no apparent relation to minimum temperature in these seasons. The most stable season in 2012–2023 was summer (JJA), when PM10 concentrations were low (20–25 μg/m^3), without significant changes in time or apparent variations in maximum temperature.

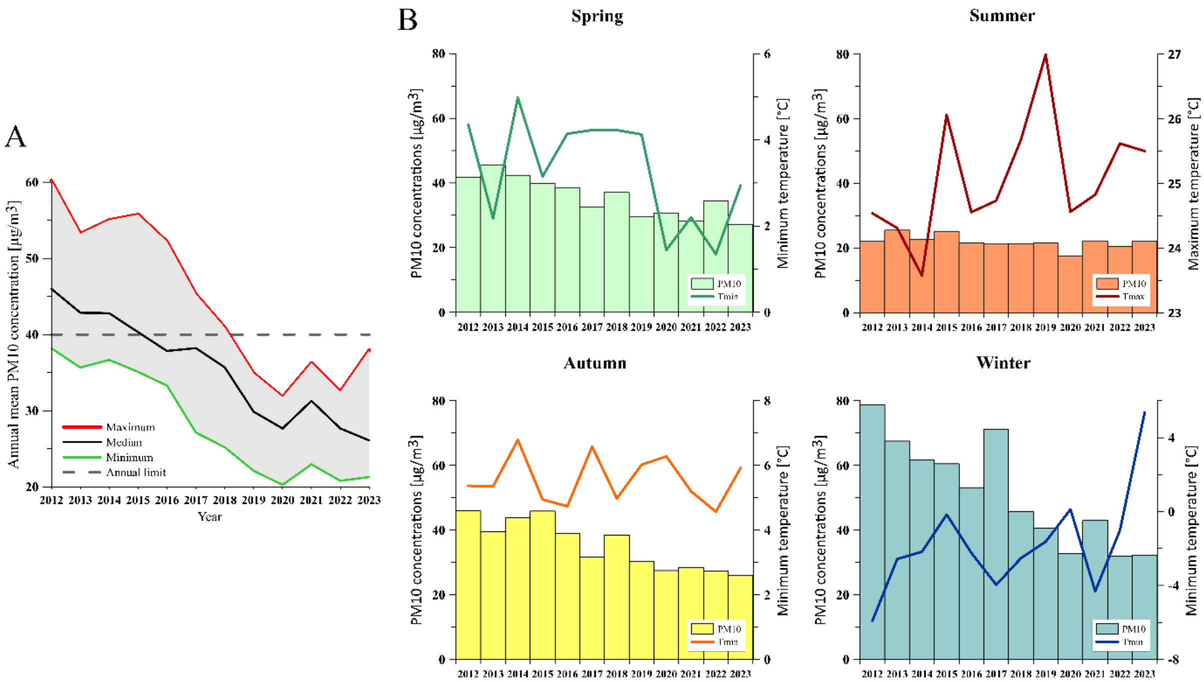

Fig. 2. A – Annual course of PM10 concentrations among stations in 2012–2023
Shaded area represents range between maximum (red) and minimum (green) station values; dotted line reflects annual limits for PM10 concentrations

B – Mean seasonal PM10 concentrations in light of minimum (autumn, winter, spring) or maximum (summer) temperatures in 2012–2023

Among all urban stations, high PM10 concentration and variability between the stations were noticed from November to March (heating season), with the highest values in February (about 57 μg/m^3 on average) (Fig. 3A). From May to September (non-heating season), the PM10 concentration (22–27 μg/m^3) and its variability among stations was low. The analysis of PM10 concentration distribution (median, quintiles, 5. and 95. percentiles and outstanding values) for each station allows us to distinguish the five most polluted stations in Central Poland: Opoczno, Radomsko, Zduńska Wola, Łódź_Legionów and Piotrków Trybunalski (Fig. 3B). But it needs to be emphasised that Łódź_Rudzka and Tomaszów Mazowiecki were right behind them.

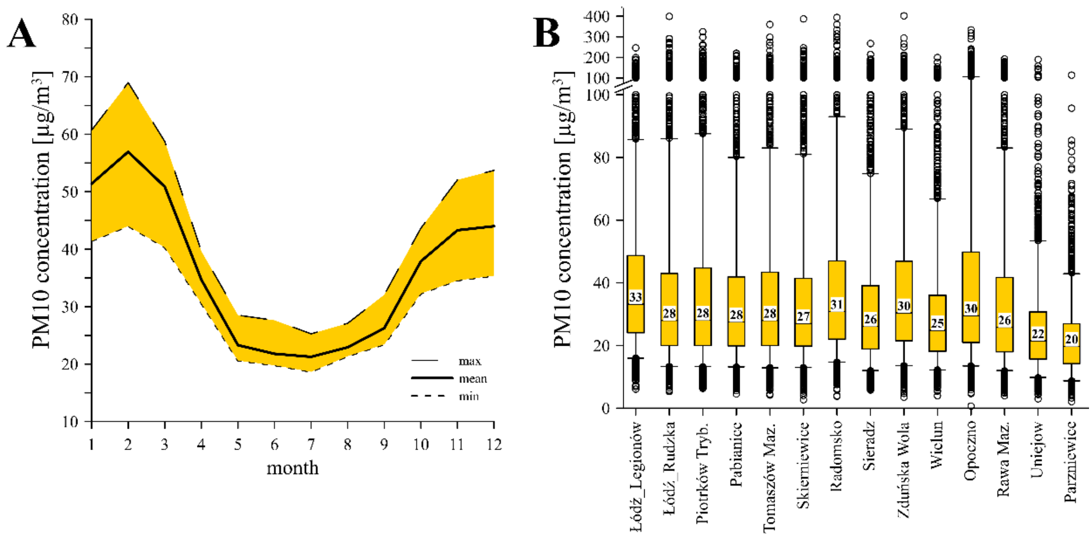

Fig. 3. Mean monthly PM10 concentrations for urban stations with:
A – range between minimum and minimum values of the stations
B – distribution of daily PM10 concentrations on each urban and non-urban station, 2012–2023
The outstanding values (circle) are illustrated for less than 5% and more than 95% of PM10 distribution.
The value inside the interquartile range box reflects the median

A more detailed illustration of changes in PM10 concentration in time concerning each station is given in Figure 4. In 2012–2015, the daily PM10 concentrations frequently exceeded 50 and 100 µg/m^3 (about 100 and 20–23 times per year, respectively). The worst situation was in 2012, when concentrations exceeded 150 and 200 µg/m^3 for several days, with the highest number of exceedance in Opoczno (27 and 7 days) and Radomsko (15 and 9 days, respectively). After 2015, the air quality started to improve gradually, and the number of 50 and 100 µg/m^3 exceedances decreased. The very high PM10 concentrations then occurred occasionally, except in 2017, when highly polluted air was present in all urban stations, which was related to a cold winter. Since 2019, some of the urban stations (Pabianice, Skierniewice, Wieluń, Tomaszów Mazowiecki and Sieradz) started to meet the limits of no more than 35 days above 50 µg/m^3 during the year, and, at the rest of the stations, this number was also significantly reduced. The consecutive years are not equal, with warmer or colder winters, which is reflected in PM10 concentration. Nevertheless, the air quality improved between 2012 and 2023. In the last years, very high PM10 concentrations (>150 µg/m^3) are noted occasionally, even in the most polluted municipalities such as Radomsko, Piotrków Trybunalski, Opoczno, Zduńska Wola or Łódź.

Study case

In this part of the study, two urban areas were more carefully analysed: Łódź and Opoczno. In Łódź, two manual stations collect the PM10 concentration information near Legionów and Rudzka streets. Based on the PM10 distribution in Fig. 3B and the number of daily limit (50 µg/m^3) exceedances in Figure 5, the Łódź_Legionów station is more polluted than Łódź_Rudzka due to its location in the city center (Fig. 6A). Nevertheless, it is the Łódź_Rudzka station where high and very high PM10 concentrations occurred considerably more frequently (Fig. 5). It was most apparent in 2012 and 2017, when considerably lower-than-average minimum temperatures were observed in February and January, respectively. So, why does the station located in the city centre, which is characterised by higher mean PM10 concentrations, less often exceed the threshold of high and very high concentrations? The Łódź_Rudzka station is situated at the foot of the slope near the Ner River and is surrounded by single-family houses (Fig. 6B), which, due to the combustion of fossil fuels in furnaces during cold weather, emit a great amount of pollution (PM10) that accumulates in the river valley. By contrast, Łódź_Legionów is surrounded by tenement houses (Fig. 6A), most of which in recent years have been connected to central heating or gas installations. This has limited

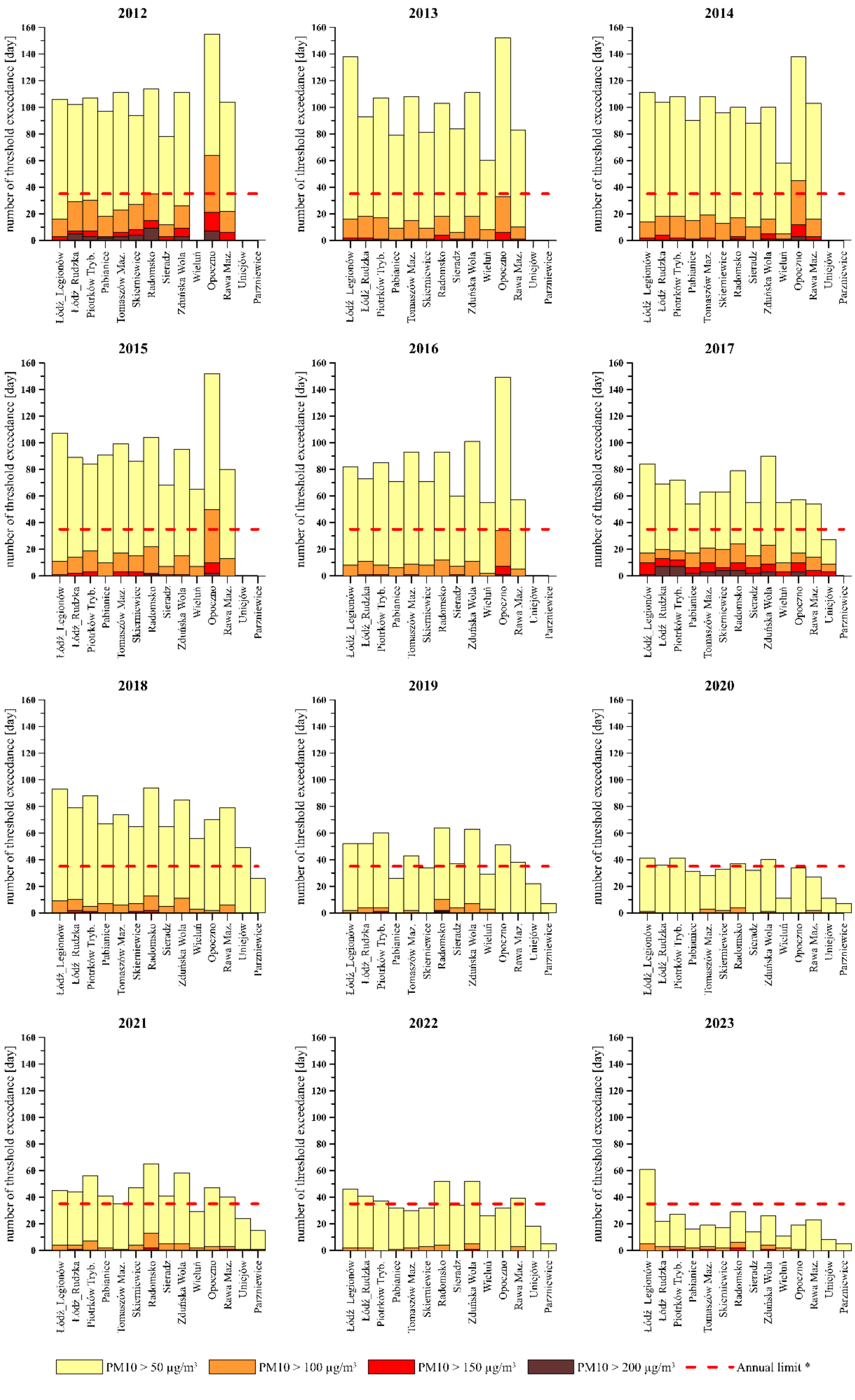

Fig. 4. Number of threshold exceedances at each station, 2012–2022
* 35 days – annual number of days when daily PM10 limit of 50 µg/m3 can be exceeded

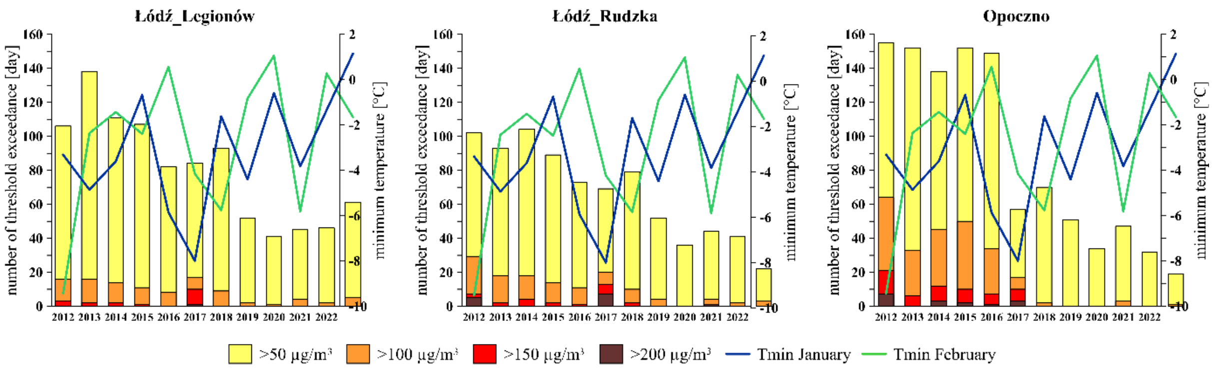

Fig. 5. Number of exceedances of selected PM10 thresholds at Łódź_Legionów (left), Łódź_Rudzka (middle) and Opoczno (right) stations in the light of the mean minimum temperatures in January and February (blue and green lines, respectively)

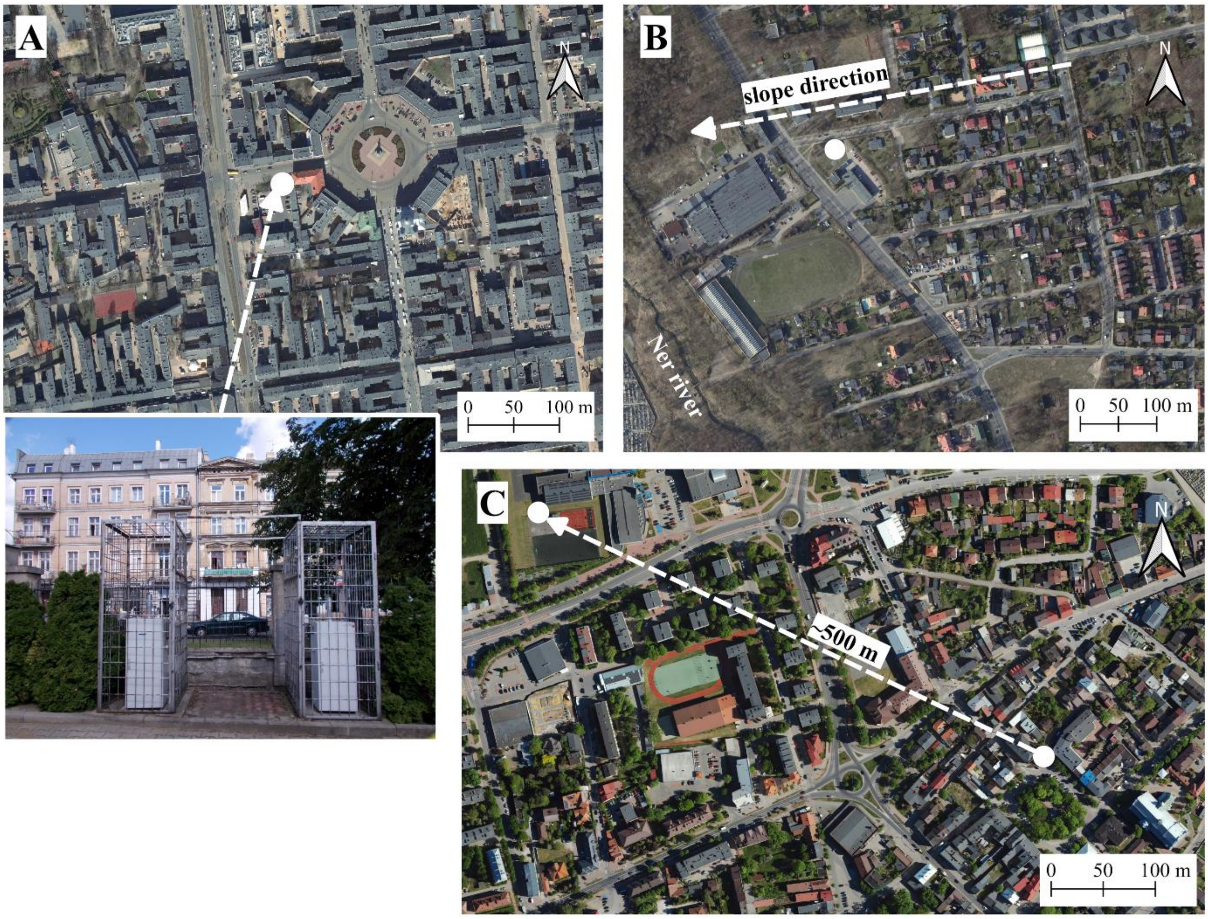

Fig. 6. Location of Łódź_Legionów (A), Łódź_Rudzka (B) and Opoczno (C) stations on the background of building character
White dots represent the situation of the PM10 measuring stations.
The base maps source is Geoportal (2023), and the station photo source is GIOŚ (2023)

the high and very high PM10 emissions. Additionally, high discrepancies appeared in 2023. The very warm winter of 2023 resulted in air quality improvement in Łódź_Rudzka. In contrast, the road reconstruction of Legionów Street (next to the Łódź_Legionów station) led to a significant increase in PM10 concentrations mostly in summer (PM10 concentrations were highest in summer and autumn [~39 µg/m^3] and lowest in winter [~35 µg/m^3]). It is worth mentioning that this summer was dry, and the station is surrounded by a deep street canyon, which does not hinder ventilation. Overall, this led to a much higher PM10 limit exceedance in 2023 at Łódź_Legionów than at Łódź_Rudzka (Fig. 5). Furthermore, due to the warm winter at the beginning of 2023, it was the first year when the PM10 concentration standards were met at all analysed stations except Łódź_Legionów (Fig. 4), where reconstruction works worsened the air quality.

Another case is Opoczno. This city was the most polluted in Central Poland until 2016, with a great number of 100 and 150 μg/m^3 exceedances (Fig. 5). After that, the air quality considerably improved, even in 2017, when the minimum temperature in January dropped significantly compared to other years. Even though the energy consumption was reduced from 2014 to 2017 by 10––20% (depending on building type) and another 10–20% to 2020 (ECOVidi 2023), it does not explain such a high drop in emissions. The main reason is the shift of the station to an unrepresentative place (Fig. 6C). Until 2017, the station was located within the main square of the city, surrounded by old single-family houses, which heavily polluted the air. After that, it was shifted by only 500 m, which can be considered a spatially minor shift. But the surroundings of the station changed considerably. Since 2017, the station has been situated in the school district, surrounded by blocks of flats connected to central heating. Therefore, a comparison of the two periods is impossible at these locations, and the central part of the Opoczno may still be highly polluted. This case provides an insight into how narrow might be the source area of PM10 measured by a station and how carefully any location changes should be planned. Otherwise, the datasets may often be incomparable.

Meteorological conditions affecting high PM10 concentrations

In the further study, the main meteorological parameters (minimum, maximum and mean temperature, wind speed and direction, sea-level pressure, precipitation and vorticity) were correlated with the daily PM10 concentrations in the five most polluted urban areas (Łódź, Piotrków Trybunalski, Zduńska Wola, Radomsko and Opoczno) with the use of Spearman's rank correla-

Table 2

Spearman's rank correlation coefficients between selected daily values of meteorological parameters: minimum temperature (Tmin), mean temperature (T2m), maximum temperature (Tmax), sea level pressure (SLP), wind speed (WS), precipitation (RR), vorticity (V) and PM10 concentrations from six most polluted stations in Central Poland (Radomsko, Opoczno, Piotrków Trybunalski, Łódź_Legionów, Łódź_Rudzka, Zduńska Wola) in 2012–2023

Month	Tmin	T2m	Tmax	SLP	WS	RR	V*
1	-0.57	-0.48	-0.54	0.27	-0.34	-0.27	-0.32
2	-0.51	-0.29	-0.43	0.30	-0.32	-0.35	-0.27
3	-0.30	0.07	-0.07	0.31	-0.32	-0.34	-0.11
4	-0.04	0.29	0.22	0.02	-0.07	-0.23	0.03
5	0.08	0.38	0.32	0.03	-0.03	-0.24	0.09
6	0.11	0.39	0.37	0.10	-0.03	-0.14	0.14
7	0.25	0.55	0.56	0.01	-0.10	-0.10	0.20
8	0.18	0.56	0.49	0.07	-0.04	-0.23	0.17
9	-0.09	0.37	0.23	0.14	-0.15	-0.24	0.04
10	-0.28	0.06	-0.11	0.37	-0.28	-0.34	-0.10
11	-0.25	-0.13	-0.22	0.24	-0.19	-0.27	-0.14
12	-0.53	-0.48	-0.51	0.37	-0.31	-0.30	-0.29

Explanation: V* – correlations for 2012–2022 tion coefficients (Tab. 2). The Łódź_Legionów, Łódź_Rudzka and Zduńska Wola stations were compared to the meteorological station in Łódź, whereas Piotrków Trybunalski, Radomsko and Opoczno were compared to the station in Sulejów due to their shortest distance to the meteorological station. Łódź_Rudzka was included in this analysis due to its very high PM10 concentration under unfavourable meteorological conditions. The correlation value was averaged among stations. The strength of the correlation differs on the seasonal or monthly scale. Generally, the highest correlations with meteorological parameters were found for winter, when the PM10 concentrations were the highest. A more detailed description of the relations between PM10 concentrations and meteorological parameters is given below for seasons characterised by the highest correlations.

Air temperature

Strong negative correlations were observed in winter for the minimum, maximum and mean temperatures (~-0.5 or lower). At most stations, the daily limit of PM10 concentration is exceeded when the Tmin drops below -2/-3°C on average, but for Opoczno it is ~2 °C (Fig. 7). Usually, when the Tmin decreases to -8/-10 °C, high and very high concentrations occur. During very cold weather conditions (Tmin<-20 °C), the PM10 concentrations were even higher than 300 μg/m^3. For the daily mean temperature, the PM10 limits in winter are exceeded when it decreases to below 1–2°C (4°C Opoczno) (Fig. 8A). The very high concentrations were noticed mostly for the T2m below -5 °C. In the case of Tmax, the PM10 limit is usually exceeded when it reaches 3–5 °C or less (9°C in Opoczno) (Fig. 9A).

The mean and maximum temperature is also highly correlated with PM10 concentration in summer (July–August). These correlations are slightly stronger in July–August (0.53–0.56) than in December–January (-0.48 to -0.53). It needs to be emphasised that the PM10 concentration limit is occasionally exceeded in the summer. The probability of its occurrence increases with temperature. It was above 17°C and 25°C for T2m and Tmax, respectively, when the PM10 threshold was exceeded. More attention should be given to Łódź_Legionów station, where summer PM10 concentration was considerably higher than at other stations. This might be explained by the road reconstruction in 2023 and the station's location near the deep street canyon of about 15 m buildings in height, which, under stable atmospheric conditions, leads to an accumulation of pollution.

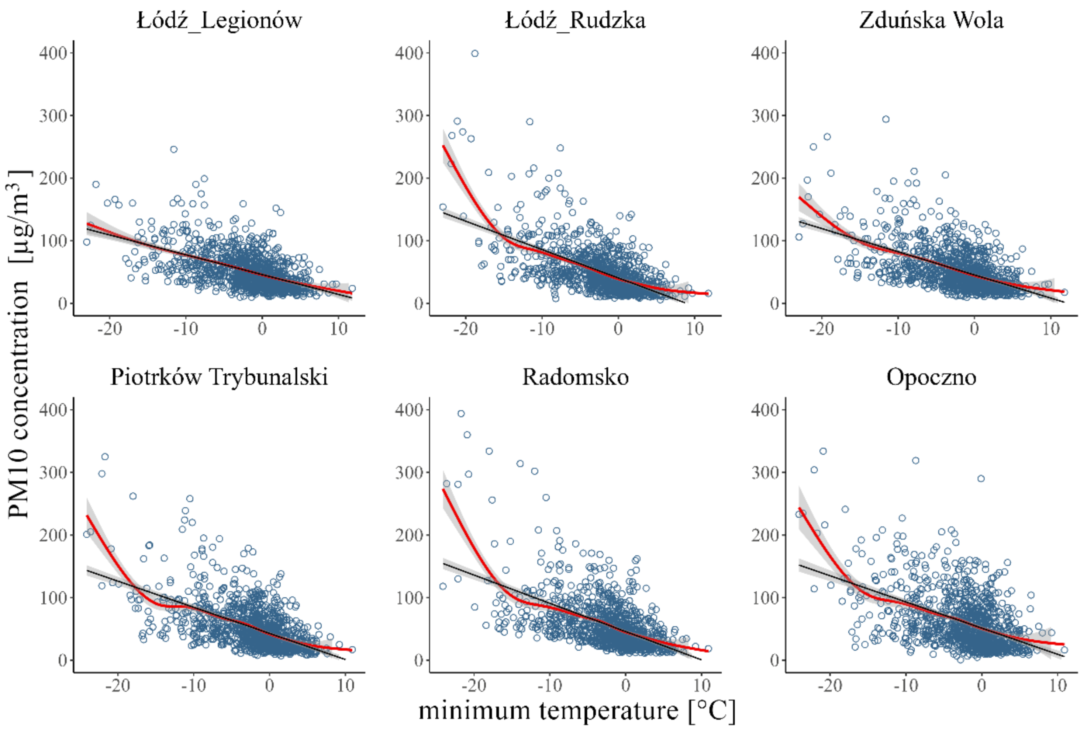

Fig. 7. Dependencies of daily mean PM10 concentrations on minimum winter temperature (DJF) for the six most polluted stations in Central Poland, 2012–2023
Solid lines represent linear (black) and local polynomial regression fitting (red) and its 95% confidence bands (grey)

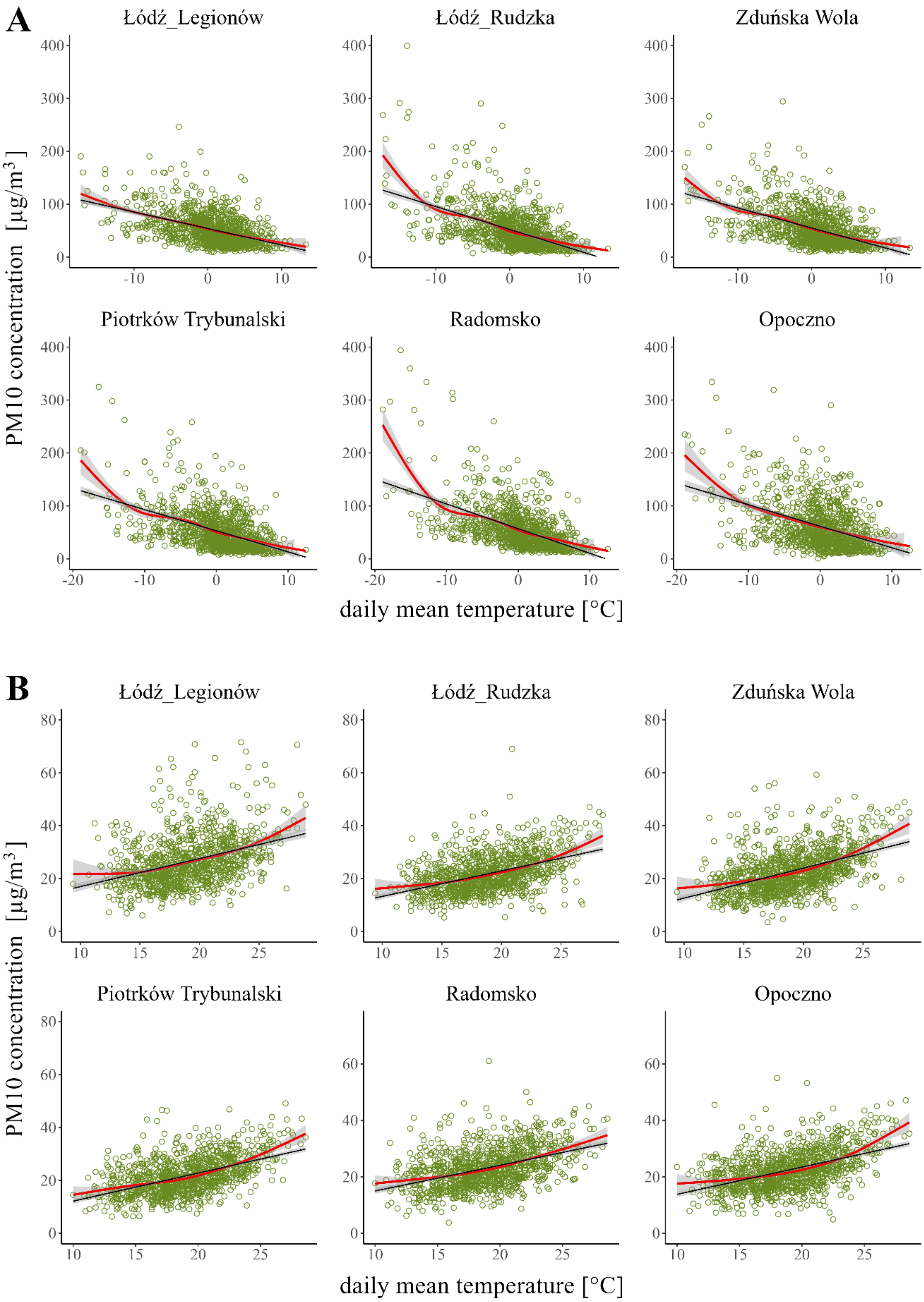

Fig. 8. Dependencies of daily mean PM10 concentrations on daily mean temperature in winter (A) and summer (B) for the six most polluted stations in Central Poland, 2012–2023
Explanations: see Fig. 7

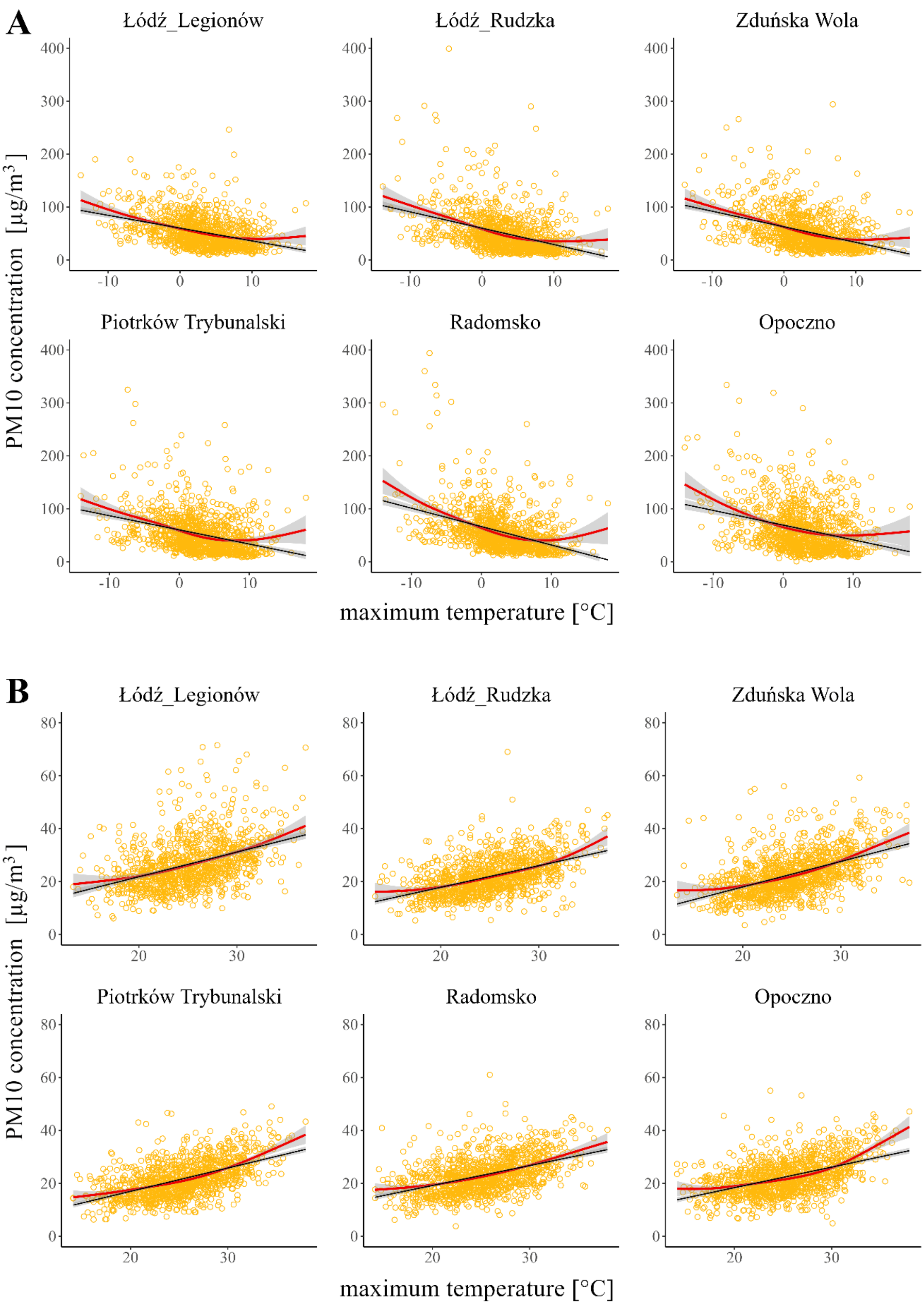

Fig. 9. Dependencies of daily mean PM10 concentrations on maximum temperature in winter (A) and summer (B) for the six most polluted stations in Central Poland, 2012–2023
Explanations: see Fig. 7

Sea-level pressure and vorticity

Sea-level pressure and vorticity indicate a significant correlation with PM10 only in winter. The correlation is moderate in strength (about 0.3), being positive for SLP and negative for vorticity. This means the high PM10 concentration usually occurs under high-pressure systems (anticyclonic weather). The daily limit of PM10 is exceeded when the SLP is higher than 1015–1018 hPa (Fig. 10A). Very high PM10 concentrations (>200 µg/m^3) were noted for SLP higher than 1025–1030 hPa. Slightly less sensitive to high SLP was Łódź_Legionów (lower PM10 concentration than other stations). The highest PM10 concentrations were observed for the vorticity, which oscillates around 0 (±10) (Fig. 10B). These are the situations of the low-pressure gradient when the air masses move slowly or stagnate over the region. Furthermore, higher PM10 concentrations were also noted for the vorticity <-20, which proved that anticyclonic weather fosters the maintenance of air pollution.

Precipitation and wind speed

The relationships of PM10 concentrations to precipitation are negative and highest in the cold half-year (from -0.27 to -0.35). The highest (moderate) correlations were found in February, August and September. A considerable PM10 decrease was noted when the daily precipitation exceeded 10 mm (Fig. 11A). Among the analysed stations, only Opoczno seems to be "more resistant" to precipitation, where high concentration occurred in some cases even when RR was >10mm. The wind is similar to the precipitation factor, which improves pollution dispersion. The correlation between the daily WS and PM10 concentration is generally weak, with the most significant values of -0.31 to -0.34 in winter. However, it needs to be emphasised that the signal (relationship) would be stronger for the hourly than daily data. Nevertheless, usually, the improvement of the air quality and low PM10 concentrations are observed when the daily WS exceeds 5m/s (Fig. 11B). However, in some cases, the limits of PM10 concentration were exceeded even for the WS>5–6 m/s or 8 m/s in Opoczno. This was probably for the situations when the city was highly polluted and associated with south-eastern air masses inflow under the high-pressure system.

Wind speed and direction vs high PM10 concentrations

The high concentrations of PM10 in winter are related to the weather type and wind direction. During the anticyclonic weather, there is a higher probability of 50 and 100 µg/m^3 limit exceedance than cyclonic weather. It is hard to indicate a wind direction with the highest probability of high PM10 concentrations. For anticyclonic weather, two sectors should be distinguished. The first is the eastern and north-eastern sector (more apparent in Zduńska Wola, Opoczno and Radomsko), and the second is the southern and south-western (more visible in Piotrków Trybunalski and Łódź). During cyclonic weather, the eastern and north-eastern sectors dominate without considerable differences between the stations (Fig. 12).

Generally, during the cold half-year (October–March), high PM10 concentrations occurred during calm weather or slight wind speed (Fig. 13). Furthermore, in all urban areas, an increase in pollution was found for the air masses inflow from the eastern sector (especially for the SE and ESE directions), but it was the most pronounced in Opoczno and Łódź_Legionów. In the case of Zduńska Wola but also Radomsko, a significant increase in PM10 concentration was noticed for the north-western air masses inflow.

Discussion

Generally, from 2012 to 2023, the concentration of PM10 in Central Poland has decreased considerably, which is in good agreement with the results observed in the whole of Poland (Wierzbińska *et al.* 2023; Zgłobicki, Baran-Zgłobicka 2024). Since 2019, the annual standard of PM10 has been met at all analysed stations. Furthermore, since then also, the daily limits in the annual view at some stations (Pabianice, Tomaszów Mazowiecki, Skierniewice, Wieluń) have not been exceeded. In 2023, partly due to the very warm winter, it was the first time when the daily PM10 standards were met at all analysed stations except Łódź_Legionów (where data were not very reliable due to road reconstruction). Without a doubt, in the last few years, the air quality in Central Poland has greatly improved. But still, in the cold half-year and especially in winter, the PM10 concentrations are relatively high. This is mainly determined by low emissions from the residential

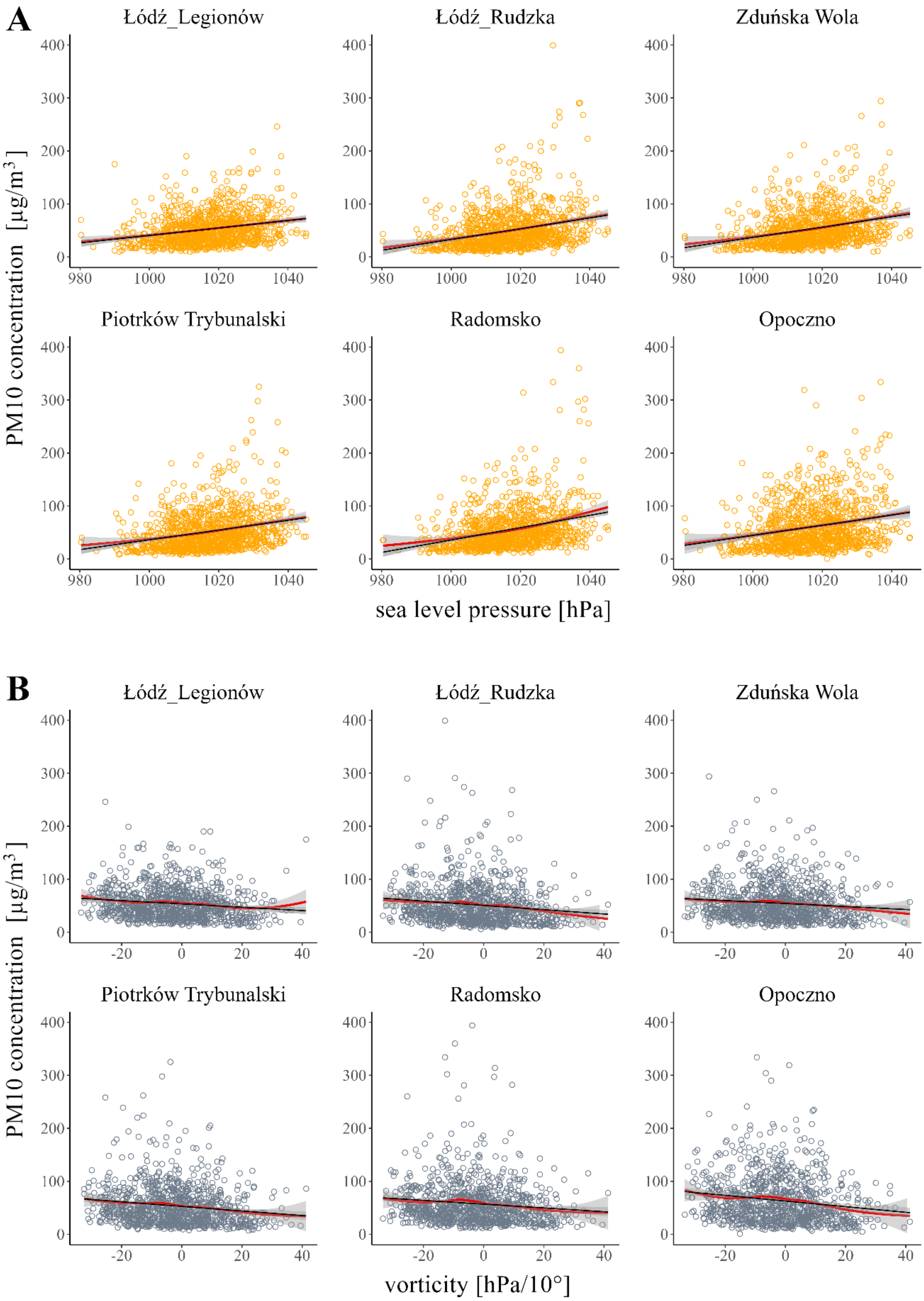

Fig. 10. Dependencies of daily mean PM10 concentrations on sea-level pressure (A) and vorticity (B) in winter for the six most polluted stations in Central Poland, 2012–2023
Vorticity calculated for central latitude of 51.5° N

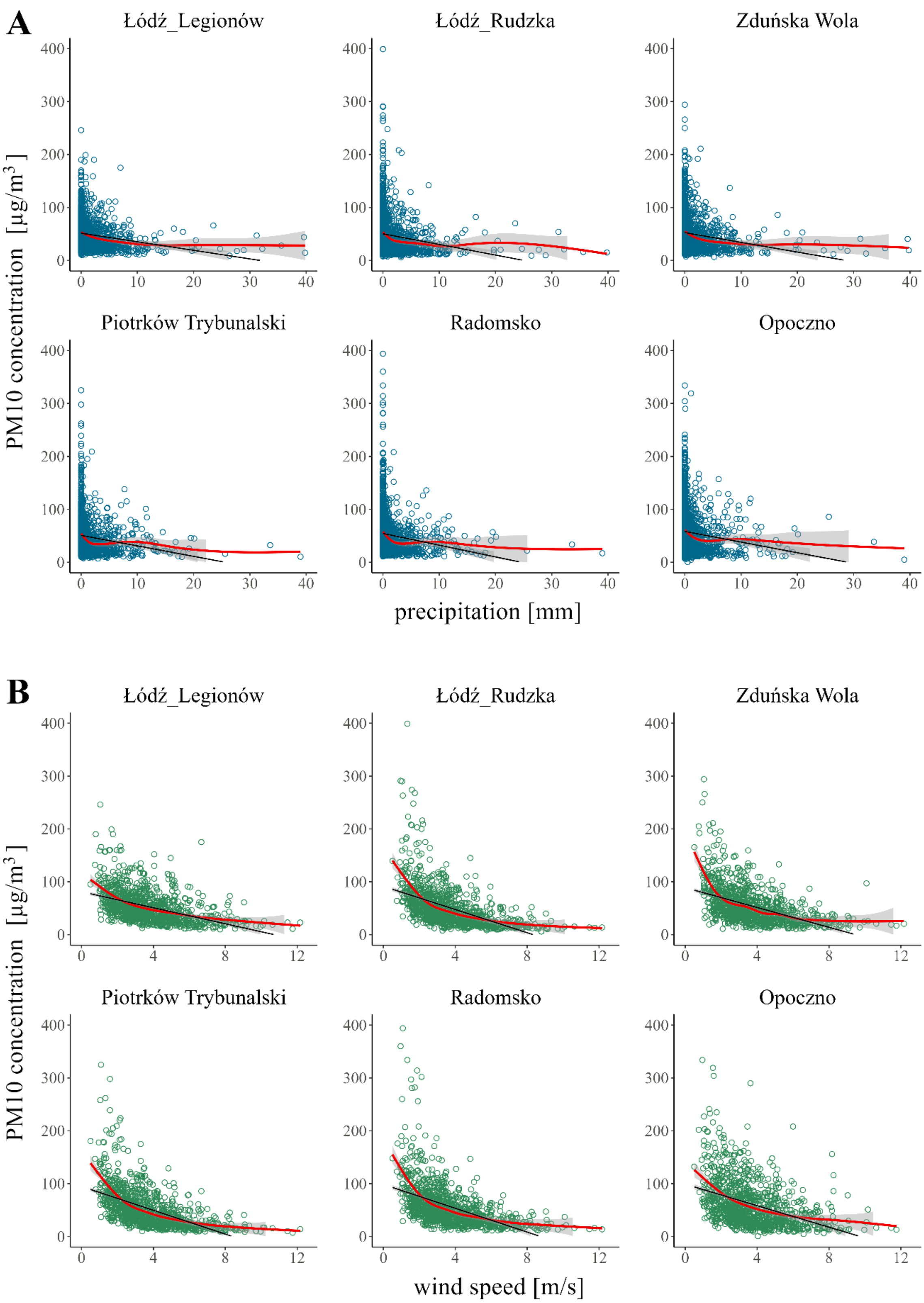

Fig. 11. Dependencies of daily mean PM10 concentrations on precipitation in the cold half-year, October–March (A) and wind speed in winter (B) for the six most polluted stations in Central Poland, 2012–2023

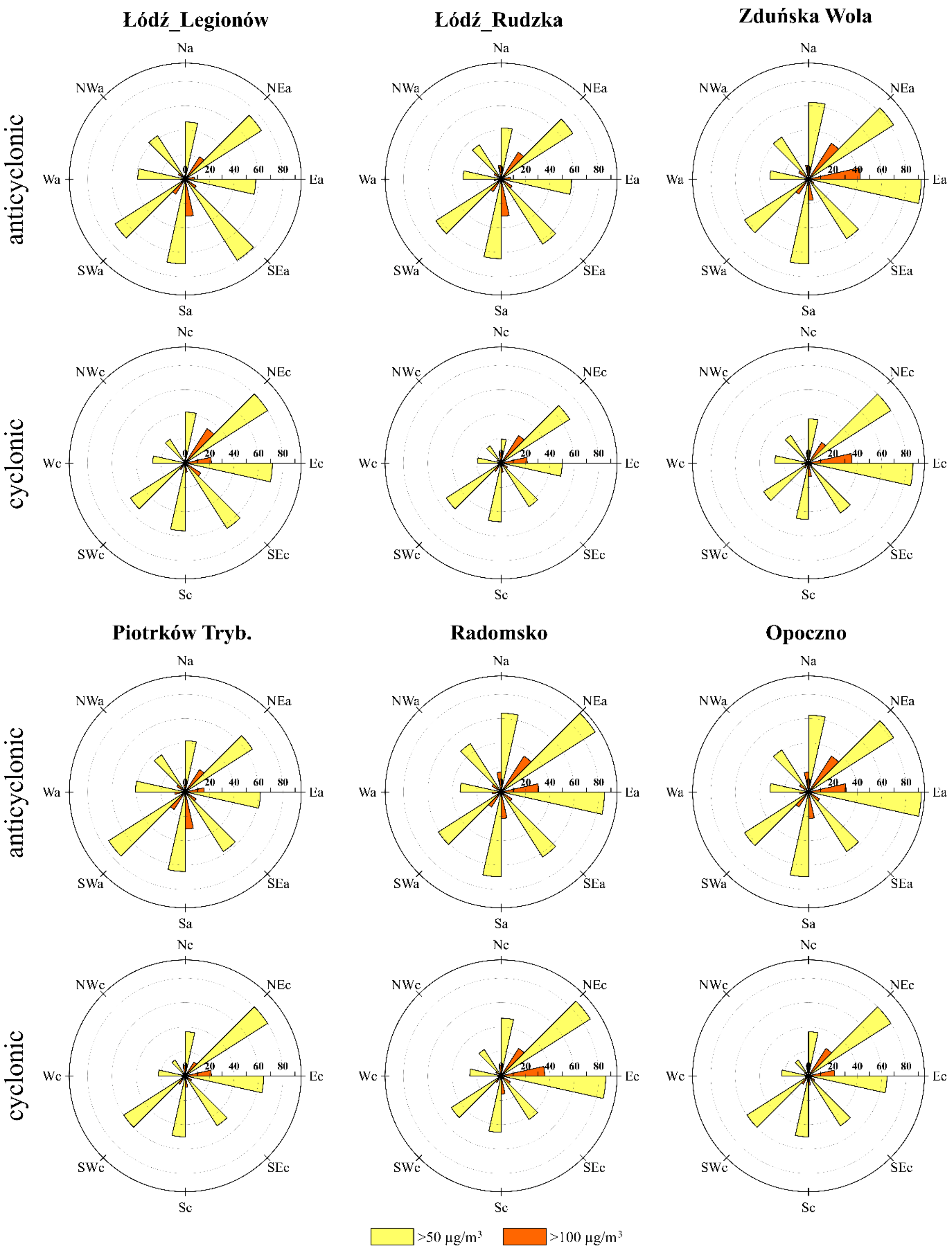

Fig. 12. Probability of PM10 limits (50 µg/m^3 and 100 µg/m^3) exceedance [%] according to weather type (anticyclonic, cyclonic) and wind direction for the six most polluted stations in winter in Central Poland, 2012–2022

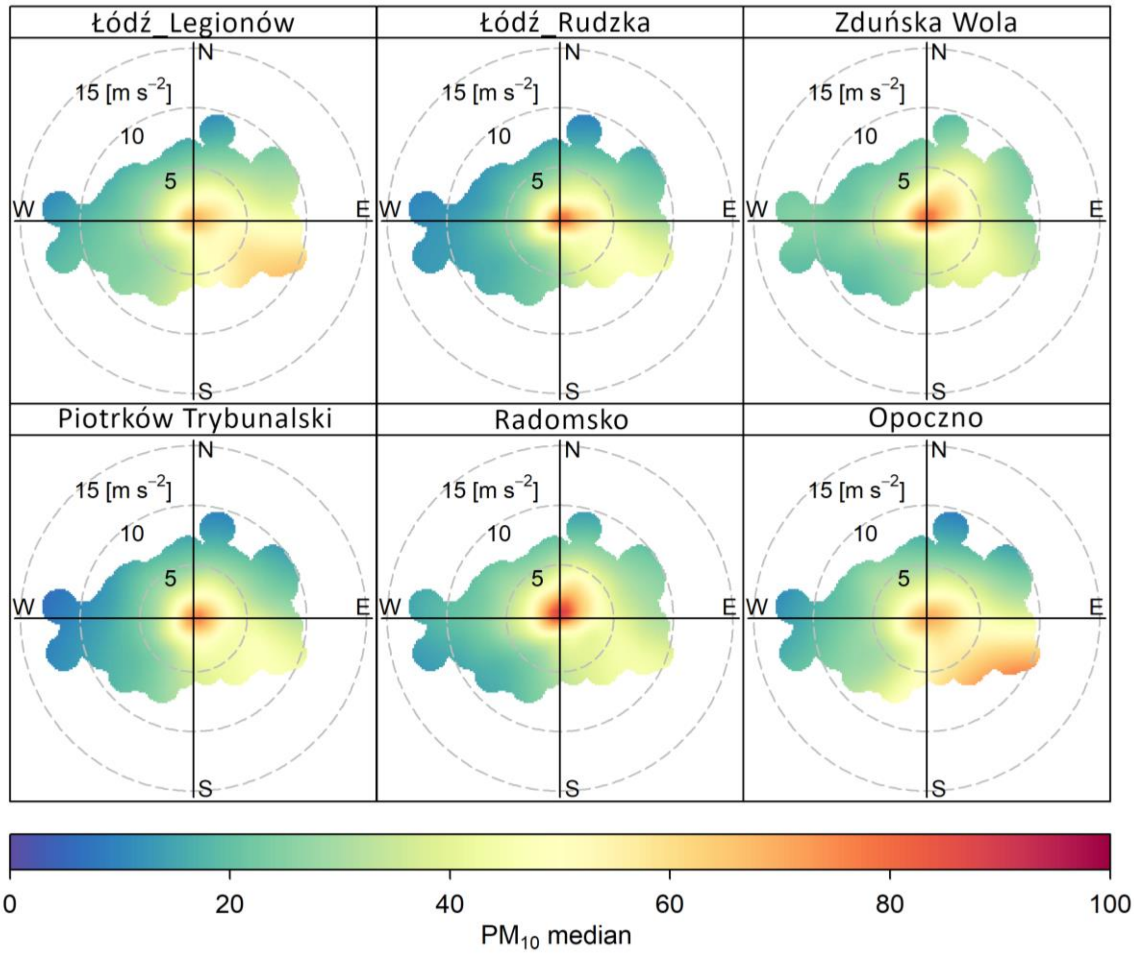

Fig. 13. PM10 concentrations in relation to wind speed and wind direction for the selected most-polluted stations in the cold half-year (October–March)

areas. The most harmful is the combustion of poor coal quality or garbage (i.e., plastic, contaminated wood, old furniture or tyres). The PM10 concentration variability in the study period allows us to select the most polluted urban areas in Central Poland, namely Opoczno, Radomsko, Zduńska Wola, Piotrków Trybunalski and Łódź.

The PM10 concentration in Central Poland is at the moderate level between the highly polluted southern part of the country (i.e., Kraków, Katowice) and the least polluted north (i.e., the Tri-City). The meridional increase in pollution in Poland has been mentioned in many studies (Jędruszkiewicz *et al.* 2017; Rawicki *et al.* 2018; Wielgosiński, Czerwińska 2020). Nevertheless, the PM10 concentration in Central Poland is diverse, and highly polluted cities such as Radomsko or Piotrków Trybunalski are on the list of the most polluted cities in Poland and Europe.

The amount of air pollution should follow the population number of the urban areas. However, this study proved that the PM10 concentrations are only slightly related to the number of inhabitants. Łódź is the only city of above 500,000 citizens in the voivodeship, but its pollution with PM10 is at the same level as or lower than much smaller cities such as Opoczno, Zduńska Wola or Radomsko of fewer than 45,000 citizens. This might be due to from several reasons. Łódź might have a higher share of houses connected to central heating or use alternative, modern sources of energy (solar panels, heat pumps, etc.). Whereas, in smaller municipalities, there might be a lower environmental awareness of inhabitants or higher poverty, forcing people to burn low-quality fossil fuels or wastes and use an old furnace. Higher pollution in small and moderate cities was also noted by Polish Smog Alert (PAS 2019). But this does not explain why Pabianice, Skierniewice or Wieluń are considerably less polluted than their respective equivalently populated cities of Tomaszów Mazowiecki, Radomsko or Opoczno.

The meteorological parameters play a secondary role in the high concentration of PM10. Nevertheless, cold winters such as 2012 or 2017 are characterised by a very rapid growth in very high PM10 concentrations, which was most apparent in Opoczno, Radomsko, Piotrków Trybunalski, Zduńska Wola or Łódź_Rudzka. A significant increase of 20% in BaP concentrations, which in Poland mostly comes from the burning of low--quality coal in old furnaces, was noted in the cold winter of 2010 in relation to the warm winter of 2020, which was reflected in higher morbidity of lung cancers (Porwisiak *et al.* 2023). Most of the high and very high PM10 concentration episodes occurred in winter under cold, anticyclone weather with the advection of the air masses from the eastern (E-NE) or southern (SW-S) sector. The high-pressure system or low-pressure gradient, limited turbulence and subsidence of the air masses hinder air circulation and pollution dispersion. Similar meteorological conditions contributing to high PM10 concentrations were observed in various urban agglomerations across Poland from the Tri-City through Poznań and Łódź, toward Kraków (Jędruszkiewicz *et al.* 2017). The presence of a strong Siberian High ridge over Poland and the inflow of eastern air masses was noted by Reizer and Juda-Rezler (2016) during the cold winters in 2009 and 2010. In Poznań and Kraków, a PM10 exceedance was observed, similarly to Central Poland, under anticyclonic weather and the advection from southern and eastern directions (Leśniok *et al.* 2010; Czernecki *et al.* 2017; Jędruszkiewicz *et al.* 2017; Pilguj *et al.* 2018). Furthermore, it must be emphasised that Opoczno, the most polluted city in Central Poland, is more resistant to meteorological factors contributing to improved air quality, such as high precipitation or wind speed. The PM10 limits are exceeded under higher temperatures in winter than in the rest of the stations.

National and local-level administrations implemented adaptation plans, which were created to improve the air quality. The “Clean Air” programme was launched in 2018 and offers grants to replace obsolete heat sources and improve insulation in single houses. However, according to the NIK (Supreme Audit Office) report (NIK 2022) from the audit, after three years of the programme, only 2.4% of buildings were insulated, and merely 2.2% of old-generation boilers were replaced with low-emission devices. So far, this program is highly insufficient, but in 2020, it was re-edited and simplified, but it will take time to see the result. Furthermore, local authorities are trying to increase green infrastructure in Poland. For example, Łódź will host the Horticultural EXPO, postponed from 2024 to 2029. Until January 2024, very limited actions have been undertaken in the revitalising area east of the Łódź Fabryczna Railway station (central city railway and bus station). But, more importantly, in recent years, more and more city areas have been sealed, i.e. the area of the rebuilt Łódź Fabryczna Railway station, the square in front of the Łódź Grand Teather. Moreover, the high-priced lots between Łódź Fabryczna and EC1 will be occupied by high-rise, densely built apartments surrounded by concrete instead of parks, which are necessary in the city center due to pollution and summer heat stress. At the same time, trees and plants growing in the ground are substituted by trees in pots, which have no chance to grow and develop their roots; the trees planted in large numbers on the city outskirts in recent years withered because no one took care of them. This is only the tip of the iceberg, which presents the wrong actions undertaken not only in Łódź but in many cities of Poland.

Conclusion

The most crucial factor for high PM10 concentrations in Central Poland is the low-level emission from residential areas (old single-family houses). Often, these houses are poorly insulated and require higher use of coal, combusted in old, insufficient furnaces. In many cases, due to high poverty or less environmental awareness of the society, poor quality of coal or other poisonous sources of heat are used for burning. Meteorological conditions play a secondary role in pollution accumulation, but they are important in wintertime for the aforementioned reasons. Firstly, colder weather increases the demand for heat, which is mainly produced in Poland due to coal and its “substitute” combustion. Secondly, higher winter emission accumulates near the ground due to anticyclonic weather and a more stable atmosphere, leading to air-mass subsidies. Furthermore, low-pressure gradient, low wind speed and limited precipitation are other meteorological conditions that favour high PM10 concentrations. These conditions might be additionally exaggerated by orography (Łódź_Rudzka case). The number of citizens is not as important factor as it seems. The same level of pollution as in Łódź or even higher might be generated in small towns such as Opoczno, Zduńska Wola and Radomsko. Nevertheless, the air quality has improved in Central Poland since 2012, and, since 2019, more and more cities have met not only the annual but also the daily standards of the PM10 concentration. But still, the emissions in winter are too high. This problem should immediately be solved by increasing environmental awareness of society and launching properly constructed plans and easily achievable grands for exchanging the heating source and better insulation not only in single-family houses but also in townhouses, tenements or other buildings that are not connected to the central heating systems or do not use alternative sources of heating.

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