

Influence of the atmospheric conditions on PM₁₀ concentrations in Poznań, Poland

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Abstract This study investigates atmospheric conditions' influence on the mean and extreme characteristics of PM₁₀ concentrations in Poznań during the period 2006–2013. A correlation analysis was carried out to identify the most important meteorological variables influencing the seasonal dynamics of PM₁₀ concentrations. The highest absolute correlation values were obtained for planetary boundary layer height ($r = -0.57$), thermal (daily minimum air temperature: $r = -0.51$), anemological (average daily wind speed: $r = -0.37$), and pluvial (precipitation occurrence: $r = -0.36$) conditions, however the highest correlations were observed for temporal autocorrelations (1 day lag: $r = 0.70$). As regulated by law, extreme events were identified on the basis of daily threshold value i.e. $50 \mu\text{g m}^{-3}$. On average, annually there are approximately 71.3 days anywhere in the city when the threshold value is exceeded, 46.6 % of those occur in winter. Additionally, 83.7 % of these cases have been found to be continuous episodes of a few days, with the longest one persisting for 22 days. The analysis of the macro-scale circulation patterns led to the identification of an easy-to-perceive seasonal relations between atmospheric fields that favour the occurrence of high PM₁₀ concentration, as well as synoptic situations contributing to the rapid air quality improvement. The highest PM₁₀ concentrations are a clear reaction to a decrease in air temperature by over 3 °C, with simultaneous lowering of PBL height, mean wind speed (by around 1 m s^{-1}) and changing dominant wind directions from western to eastern sectors. In most cases, such a situation is related to the expansion of a high pressure system over eastern Europe and weakening of the Icelandic Low. Usually, air quality conditions improve along with an intensification of westerlies associated with the occurrence of low pressure systems over

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western and central Europe. Opposite relations are distinguishable in summer, when air quality deterioration is related to the inflow of tropical air masses originating over the Sahara desert.

Keywords Air pollution · Particulate matter · PM₁₀ · Atmospheric circulation · Poznań · Central Europe

1 Introduction

Poznań is the fifth largest city in Poland with a population of 550,000, and well over a million in the greater metropolitan area. The city of Poznań (52°18′–52°30′N 16°48′–17°04′E) is located mainly on the plateau areas of the Wielkopolskie Lakeland at an elevation of 50 to 154 m amsl, covering an area of 261.91 km² (Kondracki 2002; Central Statistical Office 2016). Similarly to many other European agglomerations, Poznań needs to deal with the problem of a large concentration of particulate matter less than 10 or 2.5 μm in diameter (PM₁₀ and PM_{2.5}) (Juda-Rezler and Manczarski 2010; European Environment Agency 2015). This problem is of particular importance in central European agglomerations, especially in Polish cities (Krynicka and Drzeniecka-Osiadacz 2013; Rogula-Kozłowska et al. 2014; Rozbicka and Michalak 2015) which occupy top positions in the ranking of most polluted air in terms of benzo [a] pyrene and PM₁₀ concentrations (European Environment Agency 2015). According to data presented by the European Environment Agency (EEA 2015) the issue of elevated PM₁₀ concentrations in Europe is not restricted only to central part of the continent (where higher contribution of carbonaceous matter in PM is observed) but can be considered a more widespread problem. Episodes with high number of exceedances of the threshold values also occur in western Europe, especially in spring (European Environment Agency 2015). In this case, various sources are responsible for high concentration of PM: emission from traffic, agricultural fertilizers and central heating. Mentioned sources result in PM containing more nitrogen (Putaud et al. 2010). Average annual PM₁₀ levels in period 2008–2013 seem to be elevated in virtually every major city or urban region in Europe as well as vast areas of Italy and Benelux with annual average PM₁₀ concentrations exceeding 30 μg m⁻³ or in some cases 40 μg m⁻³ which is a EU Air Quality Directive limit imposed on the member countries.

PM₁₀ include nitrate, organic and black carbon (OC, BC), sulfate, secondary organic aerosol (SOA), as well as sea salt, and are emitted from different sources or produced via chemical reactions between gases (e.g. SO₂, NH₃) and oxidants in the atmosphere (OH, O₃) as well as other molecules that form the secondary organic and inorganic aerosol (SOA, SIA) (Fang et al. 2013; Squizzato et al. 2013). PM₁₀ has drawn more and more attention considering their impact on human health. Higher concentrations of PM₁₀ in the atmospheric air lead to increased mortality rates, more frequent diseases of the respiratory and cardiovascular systems, as well as other detrimental effects to human health (Zhu et al. 2012; Braniš et al. 2010; Dimitrova et al. 2012). In Mediterranean Basin, higher concentrations of PM are often associated with the inflow of the air from Northern Africa, which carries large amounts of Saharan dust, what increases the negative impact on human health (Mallone et al. 2011; Tobías et al. 2011). Concentrations of atmospheric PM₁₀ are therefore regulated by the European Union which sets limit values according to Directive 2008/50/EC of the European Parliament and of the Council of Europe (i.e. daily mean value of 50 μg m⁻³ for PM₁₀ cannot be exceeded more than 35 times within a year and mean annual value cannot exceed 40 μg m⁻³). In Poland, extreme concentrations thresholds of PM₁₀ are governed by the Regulation of the Minister of

the Environment of 24 August 2012 concerning levels of certain substances in the air, in accordance with Directive 2008/50/EC.

Changes in PM_{10} concentrations in the agglomerations depend on many, often interrelated, environmental and anthropogenic factors. Of the numerous elements influencing ambient PM_{10} concentration an emission of co-creating substances as well as a change in air temperature are the most important. The occurrence of temperature inversion may cause an additional accumulation of pollutants in the ground layer of the troposphere (Anquetin et al. 1999; Nidzgorska-Lencewicz and Czarnańska 2015; Romero et al. 1999). That is why in mid-latitudes there is a marked seasonality with a higher concentration in winter (Megaritis et al. 2013). In non-rural areas, road transport may significantly contribute to the creation of particulate matter by gas-to-particle conversion (Mysliwiec and Kleeman 2002; Cheng and Li 2010).

Besides local transport emission characteristics, the role of large-scale (synoptic) and local meteorological conditions, including low wind speed, lack of precipitation or low value of the mixing-layer height is commonly thought to be a key factor that influences near-surface high PM_{10} levels within cities (Chu et al. 2004; Cheng and Li 2010; Barmpadimos et al. 2012; Prządka et al. 2012; Zhang et al. 2012). Previous studies have also proven that a significant amount of airborne water vapour causes an increase in PM mass concentration, what might affect the number of exceedances of the limit values (Canepari et al. 2013).

One of the reasons for sharp changes in PM_{10} concentration can be the influx of air masses due to changes in macroscale atmospheric circulation characteristics (Wai and Tanner 2005; Demuzere and Trigo 2009; Zhang et al. 2012). Simultaneously, a change in circulation pattern impacts not only meteorological conditions but also the transport of pollutants (Karaca et al. 2009; Christoudias et al. 2012; Pey et al. 2013). Therefore, transboundary aerosol intrusions, caused by the atmospheric circulation, are an unavoidable issue for many areas dealing with the problem of air pollution (Karaca et al. 2009; Moreno et al. 2013).

Keeping the aforementioned in mind, the aims of this study are to: (a) examine the climatology of PM_{10} concentration in Poznań in various time scales, (b) identify local and regional meteorological conditions influencing PM_{10} concentration, (c) characterize potential interconnections between high PM_{10} concentration events and atmospheric circulation patterns. In addition to the above, a further aim of this study (d) is to analyze backtrajectories derived from the HYSPLIT model in order to establish the possible sources of pollutants during high-level PM_{10} episodes that are often related to synoptic scale circulation patterns (Buchanan et al. 2002; Wai and Tanner 2005).

2 Data and methods

The analysis in this paper made use of PM_{10} dataset from two stations in Poznań: Botanic Garden and Polanka. They are located ca. 8 km from each other on opposite sides of the city center (Fig. 1). The Polanka station is situated in the eastern part of Poznań, in an area with dense housing development. Botanic Garden is located in the city's western part. Two analyzed stations are characterized by urban dispersion of pollutants. Location of a station has a big importance, because of many factors in the city which can affect measurements in a small scale (Krynicka and Drzeniecka-Osiadacz 2013), e.g. crossroads (Rogula-Kozłowska et al. 2008). The Polanka station is placed near industrial plants, which are located on the eastern outskirts of Poznań. Botanic Garden is situated in the green area, which may have a local impact on the PM concentrations and the dispersion of pollution.

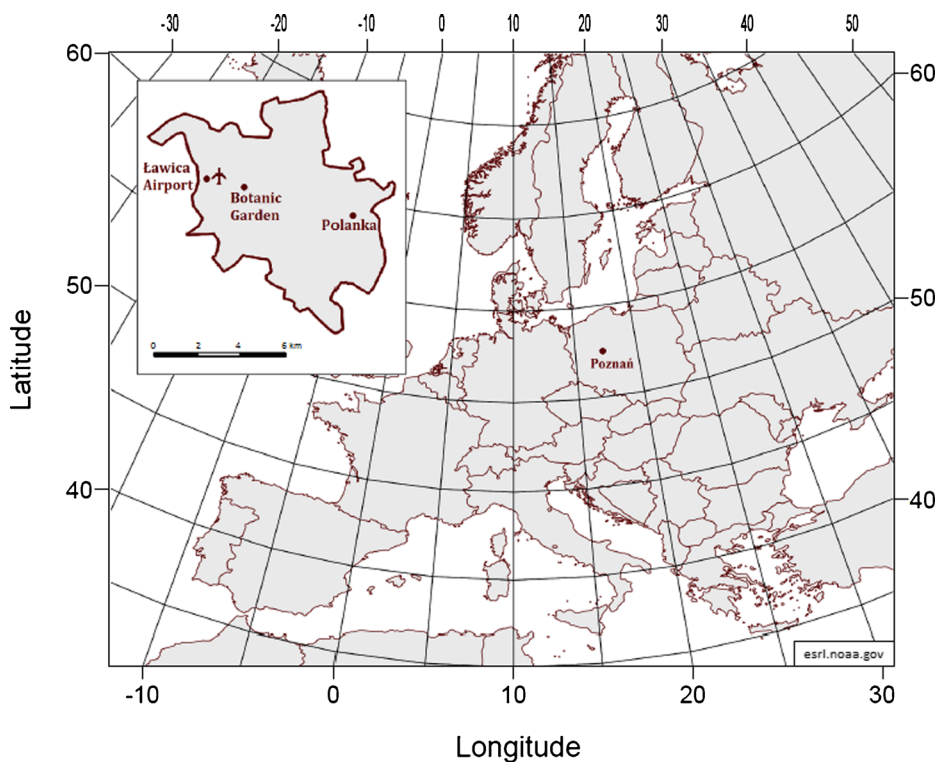


Fig. 1 Location of Poznań and the measurement stations inside the city

The investigated hourly data (for the period 2005–2013) was obtained from a website run by the Provincial Inspectorate of Environmental Protection in Poznań. The institution responsible for data dissemination assures the quality of the data through the application of measurements' and data management standards. Measurements of particulate matter were performed by automatic analyzers, which is in accordance with norm EN 12341, defined by the European Committee for Standardization. Finally, in the context of particulate matter analysis in the area of Poznań those are the only long-term data available for analysis. For technical reasons, data availability varies, and the whole dataset consists of 95.9 % (Botanic Garden) and 98.6 % (Polanka) valid hourly records. Only days with more than 75 % of valid hourly data were taken into account, and all missing record and data faults were omitted from further investigation. Additionally, the $PM_{2.5}$ dataset gathered at the Polanka station since 2009 were also taken into account as an auxiliary data to manually verify the PM_{10} measurement faults.

Since meteorological measurements on both pollution stations do not meet the World Meteorological Organization (WMO) standards for the measurement of temperature, wind, humidity, cloudiness, sea level pressure (SLP), and precipitation, those dataset were obtained from the main official meteorological station situated at the Poznań-Ławica airport (Fig. 1). Due to lack of sounding dataset that are gathered nearby Poznań, and to avoid complexity of determining planetary boundary layer (PBL) height (Seidel et al. 2010) it was decided to use the nearest grid of ERA-Interim reanalysis (Dee et al. 2011) as a dataset representing entire dynamics of near-surface air mixing. Complementary data, used as a large-scale synoptic

background, were derived from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis project version 2 (Kalnay et al. 1996; Kanamitsu et al. 2002). The mean daily SLP fields were used to detect the macro-scale atmospheric conditions favourable to high-level concentrations of PM_{10} . These datasets were used for the composite analysis on a seasonal basis which allowed the identification of the atmospheric circulation patterns associated with circulation types favourable to high PM_{10} concentration values. Additionally, Ward's (1963) minimum variance method was applied when significant varying synoptic patterns were detected during a particular season, and the recognized patterns were different from the ones obtained in a seasonal mean composite analysis.

To evaluate potential sources of pollutants triggered by air mass advection, 643 simulations were prepared and run in the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph 2003). The previously described NCEP/NCAR reanalysis was then used as meteorological input for running the simulations in selected days with exceedance of daily PM_{10} levels. Each HYSPLIT simulation consists of 48 h-long backtrajectories (with 1-h intervals) at arrival altitude of near-surface level (10 m above ground). For selected cases of summer episodes with high PM_{10} concentrations, a few extended HYSPLIT simulations were conducted to detect source emission areas influencing air dustiness within the Planetary Boundary Layer (Oke 1995) over Poznań.

All calculations and statistical procedures were carried out using the R programming language (R Core Team 2014) and its packages: 'openair' (Carslaw and Ropkins 2012, 2014) dedicated to the analysis of air pollution data, and 'ncdf4' (Pierce 2013) which provides a high-level R interface for Network Common Data (NetCDF).

3 Time variation of PM_{10} concentration in Poznań

The analysis of concentrations of annual, seasonal, and monthly PM_{10} and $\text{PM}_{2.5}$ within a multi-year period (2005–2013) at two measuring stations shows a similar course. In the case of annual concentrations, the highest values were recorded in 2011 at both Polanka and Botanic Garden. The lowest values in the Botanic Garden occurred in 2013, and Polanka in 2005 (Fig. 2). Winter is the season with the largest concentration of PM_{10} in Poznań, whereas in summer PM_{10} concentration is the smallest. However, there are certain deviations from such regularity, as observed in the case of an anomalously cold November 2011, with monthly mean values of PM_{10} oscillating around $80 \mu\text{g m}^{-3}$ (Fig. 2).

In terms of monthly mean distribution, the maximum concentration (over $50 \mu\text{g m}^{-3}$) was observed at both stations in February (Fig. 3). The minimum values in the monthly means according to station occurred in June (Botanic Garden) and July (Polanka), with a PM_{10} monthly means of around $20 \mu\text{g m}^{-3}$.

The highest values in a week-cycle are observed on Tuesdays and Wednesdays (around $32\text{--}36 \mu\text{g m}^{-3}$). The minimum values usually appear on Sundays and Mondays ($30\text{--}32 \mu\text{g m}^{-3}$). The observed week-cycle may suggest mid-term inertia (ca. 1 day lag) of near surface PM_{10} total concentration in a particular day in relation to the assumed course of pollution emissions.

In terms of subdaily course of particulate matter concentrations, a slightly higher concentration may be observed in Polanka. The daily course of PM_{10} concentration is a clear reaction to increase in traffic volumes in the morning (around 6–8 UTC), although this reaction is hardly noticed during afternoon rush hours (around 14–17 UTC). It could be estimated that the

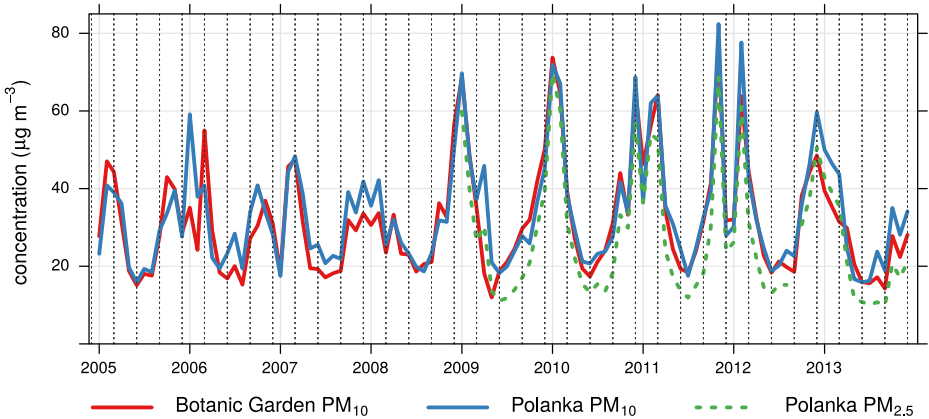


Fig. 2 Monthly mean concentration of PM₁₀ in the period from 2005 to 2013. Vertical dashed lines for meteorological seasons

contribution of mobile transportation to PM₁₀ and PM_{2.5} concentrations is probably somewhat bigger than the difference in PM₁₀ concentrations between Sundays (when significantly smaller traffic is observed) and weekdays during the corresponding rush hours (up to 7–8 µg m⁻³ on average, i.e. at least 20–25 % contribution to the whole PM₁₀ concentrations). This contribution might be even higher if improving effect of increasing PBL height in morning hours, and thus improving ventilation condition, were taken into account.

Similarly, as detected in the case of the annual cycle, the diurnal cycle of PM₁₀ level is negatively correlated with the typical course of air temperature. The heating systems' increased activity after sunset together with lowering PBL height (Oke 1995) causes an uninterrupted

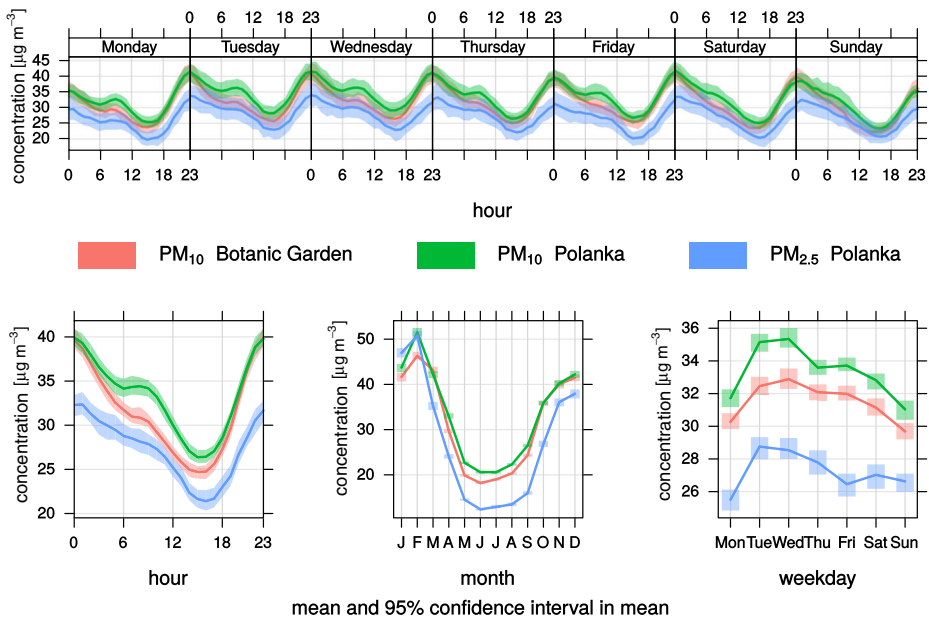


Fig. 3 Hourly, monthly, and weekday time variation of PM₁₀ and PM_{2.5} concentrations (µg m⁻³) in Poznań during the period 2005–2013. Hours given in UTC time

and sharp increase in PM_{10} concentration, with the maximum observed around midnight regardless of weekday (Fig. 3). A slightly lower demand for heating capacity after midnight and stabilizing of nocturnal PBL causes a slow decrease in PM_{10} concentration which is observed until morning rush hours.

4 Influence of meteorological conditions on daily PM_{10} concentrations

Analysis of the relationship between concentration of PM_{10} and meteorological conditions is very complicated and the mutual relations are highly nonlinear, e.g. due to the significant impact of meteorological conditions on human activity, bringing about different emission levels of PM_{10} , as well as different atmospheric dispersion properties that accompany such events. Previously described situations, e.g. with the need for domestic heating or transportation features during morning and afternoon rush hours (workdays vs. holidays, etc., Fig. 3) and PM_{10} inertia, might point to some problematic issues related to detecting interactions between natural and anthropogenic conditions influencing instantaneous concentrations of PM_{10} . Moreover, there is a high level of uncertainty related to PM_{10} concentration measurements on a sub-daily time scale (Fig. 3). Therefore, the authors have decided to use only daily means in the following study (calculated as arithmetical mean value for Poznań).

The correlation analysis shown in Fig. 4 and Table 1 clearly confirms the previously obtained results for other European areas (Draghicescu and Ignaccolo 2005; Holst et al. 2008), where temporal autocorrelation is often a crucial factor that influences the daily means concentration of PM_{10} . Due to high variability in the annual cycle (Fig. 3), the analysis presented below (Fig. 4) was carried out on a seasonal basis to additionally identify differences between particular seasons.

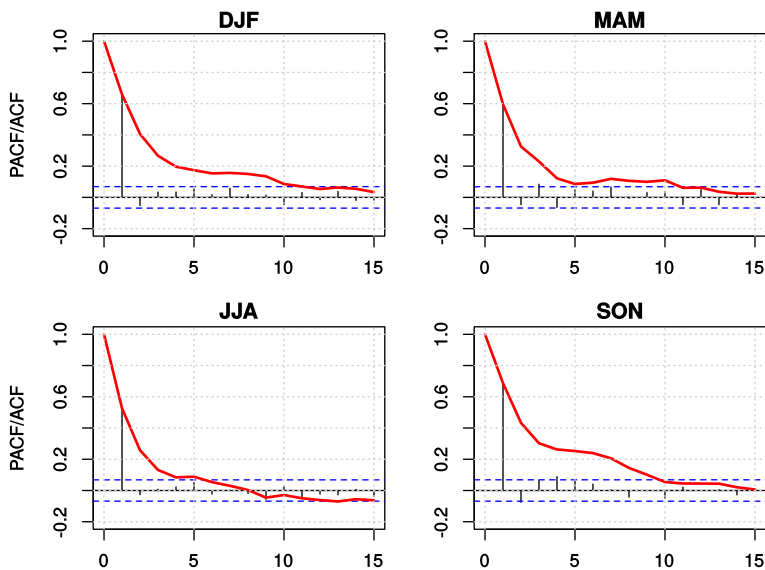


Fig. 4 Temporal autocorrelation (ACF - red line) and partial autocorrelation (PACF - black needles) dependencies of PM_{10} daily concentrations in Poznań in particular seasons (DJF - winter, MAM - spring, JJA - summer, SON - autumn)

Table 1 Relationship (Pearson correlation coefficient values) between meteorological variables and PM₁₀ mean daily concentrations in Poznań (2006–2013)

Meteorological variable and abbrev.	DJF	MAM	JJA	SON
Average planetary boundary layer height (PBL_avg)	-0.57	-0.49	-0.25	-0.65
Maximum planetary boundary layer height (PBL_max)	-0.48	-0.24	0.06*	-0.50
Minimum planetary boundary layer height (PBL_min)	-0.51	-0.28	-0.32	-0.41
Maximum temperature (Tmax)	-0.51	-0.18	0.50	-0.17
Minimum temperature (Tmin)	-0.56	-0.37	0.44	-0.37
Average temperature (Tavg)	-0.56	-0.26	0.54	-0.27
Wind speed average (ws)	-0.52	-0.39	-0.44	-0.51
Sea Level Pressure average (SLP)	0.26	0.26	0.11	0.30
Precipitation occurrence (>0.1 mm/day) (Prec.)	-0.32	-0.32	-0.33	-0.40
Average total cloudiness (Cloud.)	-0.33	-0.32	-0.33	-0.32
Average low cloudiness (LowCloud.)	-0.27	-0.29	-0.41	-0.28
Max. daily wind (incl. Wind gust) (max wind.)	-0.42	-0.31	-0.27	-0.44
Average zonal vector wind component (U)	-0.43	-0.23	-0.37	-0.38
Average meridional vector wind component (V)	0.06*	0.14	0.21	0.19

*p-value >0.05

Depending on the season, the autocorrelation (ACF) (1-day lag) coefficient varies from 0.54 (summer) to 0.70 (autumn). Those values decrease for longer lags, the fastest in the summer season, where even a 4-day lag is not statistically significant according to the F-test. In other seasons, the temporal autocorrelation statistics are still significant even on a more than a week time lag despite their values being low ($r \leq 0.2$) (Fig. 4). Even if the autocorrelation values are not very high for a few days lag, the obtained results may point to a high inertia of PM₁₀ concentration and its order of magnitude in particular seasons. However, the partial ACF (PACF) values only indicate a strong relation for a 1-day lag and according to F-test every next step is not statistically significant (Fig. 4).

The importance of a single meteorological element according to the correlation coefficients is weaker than the temporal autocorrelation presented above. The highest correlations are usually detected in terms of daily mean wind speed, which is negatively correlated with the concentration of PM₁₀ and corresponds to ventilation conditions in the city. The correlation coefficients for the mean wind speed vary from -0.52 in winter to -0.39 in spring, and are slightly higher in comparison with the maximum daily wind speed (including wind gusts if observed, Table 1). The zonal (east-west) wind vector component exhibits significantly higher importance (correlation coefficients of up to -0.43 in winter) than the meridional (north-south). This indicates that the ventilation and dispersion conditions affecting PM₁₀ concentration are related to a similar degree for both wind speed and wind direction. To determine this interrelation, a pollution wind rose analysis was carried out (Carslaw and Ropkins 2012, 2014).

The highest concentrations of PM₁₀ in Poznań occurred in a non-windy or almost non-windy situation (Fig. 5), which is also favourable towards creating a temperature inversion in a vertical profile of planetary boundary layer (Oke 1995). Usually, the highest concentrations are observed when prevailing winds blow from the eastern sector, and there are often long-lasting episodes with a very small wind speed and low elevated PBL height which is often observed in

winter (Nidzgorska-Lencewicz and Czarnicka 2015). In summer, winds of moderate strength from the southern sector create favourable conditions for higher concentrations during this time of the year. Noteworthy is the effect of wind on PM_{10} accumulation in spring, when the highest values are observed during the influx of eastern and south-east winds of moderate strength (Fig. 5). In every season, (prevailing) winds blowing from the western sector cause the smallest concentrations of PM_{10} in Poznań, and those values tend to decrease with increasing wind speed. This regularity is significantly weaker for eastern directions which occur less frequently, ca. 20 % of days in a year according to Woś (2010).

Besides anemological conditions, the daily mean PM_{10} concentrations clearly react to changes in the ambient air temperatures (minimum, maximum, and average) for all seasons. For winter, spring, and autumn seasons, the PM_{10} concentrations mostly increase with decreasing air temperature, while in the summer season this tendency is reversed (Table 1).

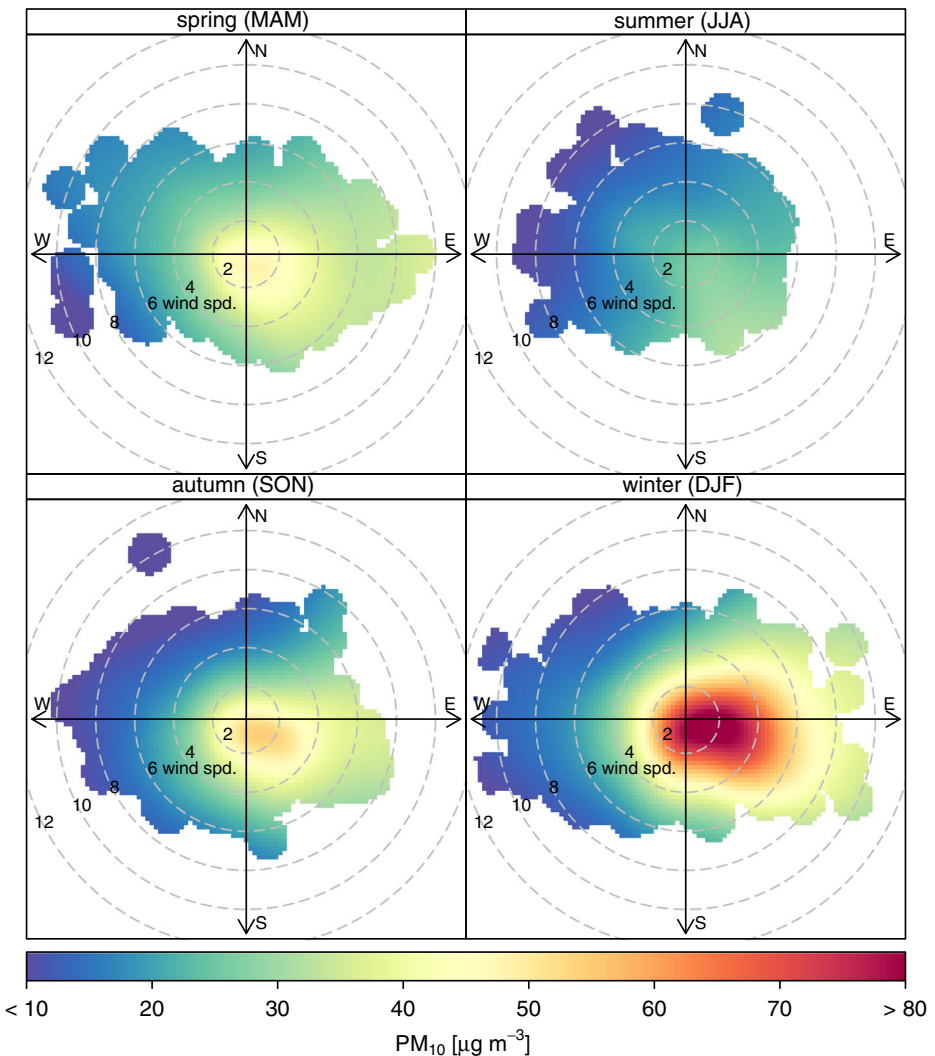


Fig. 5 Daily mean PM_{10} levels in Poznań depending on wind speed and wind directions

This may reflect the potential contribution of (anthropogenic) heating systems and other environmental conditions favourable to higher concentrations of PM₁₀ occurring during cold episodes. This is also confirmed by the lowest correlation coefficients obtained for the winter season ($r = -0.56$), while for spring and autumn seasons the strongest interdependence ($r = -0.37$) is found for minimum air temperature.

Wet deposition and the mechanism of scavenging of the PM₁₀ from the atmosphere during days with precipitation also play a significant role in reducing PM₁₀ levels. According to previous studies, it is a meteorological variable that exerts “a distinct influence on PM₁₀”, especially in cases of high-level episodes, and simultaneously weakens the importance of other meteorological variables like mixing layer height (Holst et al. 2008). During the period of analysis 41 % were wet days and the calculated Pearson’s correlation coefficients varied seasonally from -0.40 to -0.32 . After transforming the precipitation data into binary form (i.e. 0 - no precipitation, 1 - day with precipitation) and re-calculating with the Spearman rank-order, correlation values decreased (depending on season) at up to -0.44 .

As presented in Table 1 atmospheric stability classes, represented here by the PBL height, correlate (among other meteorological parameters) the highest with PM₁₀ concentrations (except summer season). However, it must be kept in mind that strong correlations (e.g. $r = -0.65$ in SON) are often the result of cross-correlation of other meteorological parameters influencing PBL characteristics such as: air temperature, SLP, cloudiness and wind speed. For example, PBL height is more correlated with wind speed ($r = 0.66$) than with PM₁₀ concentration ($r = -0.65$) in autumn season. This effect of cross-correlation is also clearly seen for other meteorological variables influencing PM₁₀ concentration like e.g. temperature indices, precipitation with cloudiness, etc. This implies that statistical modeling of PM₁₀ concentration at a daily time-scale is possible with a reasonable precision, but would require very careful selection of potential predictors to avoid effect of collinearity and overfitting.

5 Exceedances of the PM10 threshold values

In the Poznań agglomeration, it is observed that the maximum permissible concentration of PM₁₀, as specified in the European Union Directive 2008/50/EC, is frequently exceeded. Although the alarm level for instantaneous values of over $200 \mu\text{g m}^{-3}$ is only occasionally trespassed (on average: 0.55 days/year), while the mean annual values are slightly below the limit of $40 \mu\text{g m}^{-3}$, the 24-h PM₁₀ threshold value of $50 \mu\text{g m}^{-3}$ is exceeded every year with frequency far above the recommended value (35 occurrences) - from 49 days (in 2013) to 103 days (in 2011). The average number of days per year with threshold exceedance at any of Poznań’s stations is 71.3 (Fig. 6). Those statistics may vary slightly depending on local conditions and data availability for certain years. Polanka is the station where PM₁₀ concentration is most frequently exceeded. After numerous exceedances in 2011 accompanying anomalously cold winter (Table 2), subsequent years showed a gradual decline in exceedance frequency. The smallest number of exceedances was recorded in the hottest year 2008 (39). Still, this value was far above the acceptable legal limits. Generally, there has been a slow decrease in the total number of exceedances observed in the last few years. This may be partly addressed with an observed decrease in the amount of particulate matter emission from about 900 t/year to 400 t/year, which is similar to the rate of change observed all over the country (Table 2) (Central Statistical Office 2016). For this reason it can be supposed that the observed slow decrease in the total number of PM₁₀ concentration exceedances is caused both by

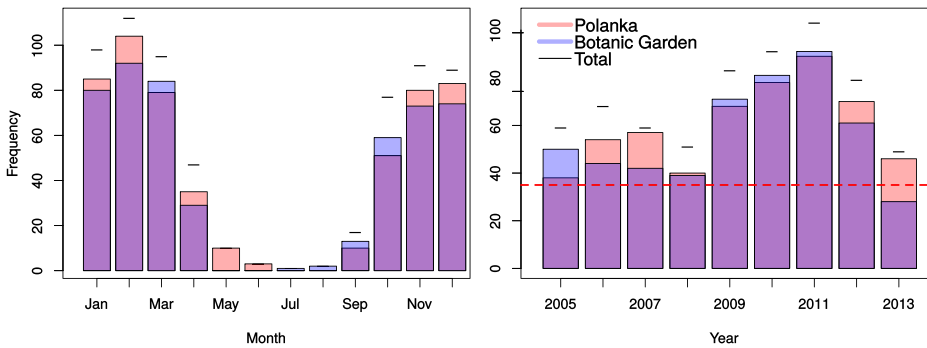


Fig. 6 Number of monthly (*left*) and annual (*right*) PM₁₀ exceedances above 50 µg m⁻³ in Poznań (2005–2013). Red dashed line denotes acceptable standards, as set by Directive 2008/50/EC

decrease of emission and the increase of temperature during cold part of year (Megaritis et al. 2013) especially after years 2010–2011.

The lowest air temperature in February is responsible for the highest number of exceedances in this month. From November to March, PM₁₀ concentrations of over 50 µg m⁻³ are reported on over 36 % of all days during that period, peaking in February when this value increases to 44 % of days. On the other hand, the summer months report only sporadic exceedances of PM₁₀ daily limits. In the period from June to August, there were only 6 such days (in 9 years) recorded (Fig. 6).

The analysis of exceedance events with daily mean PM₁₀ concentration of over 50 µg m⁻³ in Poznań shows that such cases tend to occur often during a couple of days in a row, especially in situations with a presence of stable high pressure atmospheric SLP pattern, which favours thermal inversion conditions in the atmosphere’s vertical profile and lowering of PBL height (Holst et al. 2008; Nidzgorska-Lenciewicz and Czarnecka 2015). The longest episodes of high PM₁₀ concentrations are observed mainly in winter and may last even up to 22 days anywhere in Poznań (20 days in the Polanka station), but 12–16 day-long episodes (6 occurrences) are more frequent.

The contribution of single days in the total number of days with concentration of PM₁₀ above 50 µg m⁻³ varies from 24.9 % in the Polanka station to 35.1 % in Ogrody. However, while taking into account the maximum daily mean value recorded at any of the analysed stations, the contribution of high concentration episodes lasting more than 1 day in the Poznań agglomeration reflects up to 83.7 % of all analysed situations (Table 3). This is caused by cases where the consecutive days above limit on a single station are separated by 1–2 “non-exceedance” days, which are simultaneously above the threshold value on the other station.

Table 2 The annual dust emission for area of Poznań county and city of Poznań - A, and the percentage share of dust emission in total emission for Poland - B. Winter and annual temperature anomalies calculated against years 1971–2000

	2005	2006	2007	2008	2009	2010	2011	2012	2013
A (tons /year)	858	784	846	920	497	431	488	439	396
B (%)	0.78	0.76	0.89	1.20	0.81	0.69	0.85	0.84	0.80
DJF anomaly (°C)	+0.4	-2.2	+3.7	+2.8	-0.3	-2.6	-2.6	+0.2	-1.0
Annual anomaly (°C)	0.6	1.1	1.6	1.7	0.7	-0.8	1.1	0.8	0.7

6 Meteorological conditions conducive to the emergence and disappearance of PM₁₀ threshold value exceedances

As previously shown, the concentration of pollutants strongly depends on atmospheric conditions (Table 1), which in mid-latitudes throughout an entire year are largely related to the dynamics of macro-scale atmospheric circulation. The patterns of these changes may be expressed as the long-term mean and composite anomaly maps of sea level pressure in particular seasons of the year for the days with PM₁₀ concentration above limit (50 $\mu\text{g m}^{-3}$).

When analysing the influence of meteorological conditions on the concentrations of PM₁₀, it is crucial to recognize their overall pattern (Fig. 7) and the role of long-distance transportation (Figs. 8 and 9) coinciding with the episodes of PM₁₀ daily threshold (50 $\mu\text{g m}^{-3}$) exceedances. It is also important to recognize the state of synoptic situation which favours disappearance of high PM₁₀ concentrations. Therefore, this analysis followed a twofold approach. First, the anomalies of meteorological conditions (selected variables) calculated against mean values for years 2005–2013 were analysed for both aforementioned cases (occurrence and cessation of exceedances) at the Polanka station (Tables 4 and 5). Secondly, daily composites of SLP over the Euro-Atlantic region coinciding with the disappearance of PM₁₀ exceedance events were analysed in terms of both absolute values and SLP anomalies (Fig. 10). This was applied on a seasonal basis to account for possible variations in the meteorological variables' influence. What must be mentioned is a small number (6) of daily PM₁₀ threshold exceedances during summer which yields the possibility of biased/skewed conclusions with respect to this season. This is apparent in the pattern of anomalies of analyzed meteorological variables (Table 4) where the absolute values stand out quite prominently.

6.1 Meteorological conditions accompanying exceedance of daily PM₁₀ standards

In terms of inducing exceedance of PM₁₀ norms (Table 4), somewhat conspicuous is a substantial negative anomaly of the zonal wind speed vector component (*u*) with values of over 2 m s^{-1} (in winter even beyond 3 m s^{-1}) lower than average. This indicates that the development of eastern advection is a common feature that coincides with the high PM₁₀ levels. This is accompanied by higher-than-average SLP values, suggesting the presence of a high-pressure system over the area. Also, there is an overall decrease in average wind speed by ca. 1 m s^{-1} and wind gusts (of over 2 m s^{-1} , with the exception of JJA) that indicate almost non-windy situations what stay in agreement with findings presented in the Fig. 5. Thermal

Table 3 Number of consecutive days with exceedance of the maximum permissible concentration of PM₁₀

Total number of consecutive days crossing threshold value of 50 $\mu\text{g m}^{-3}$	Number of events	Total number of days	Percentage of total days above 50 $\mu\text{g m}^{-3}$	Cumulative % of total days above limit
1	105	105	16.28	16.28
2	55	110	17.05	33.33
3–5	62	231	35.81	69.14
6–10	14	96	14.88	84.03
11–15	5	65	10.08	94.11
>15	2	38	5.89	100.00

condition anomalies also seem to be characteristic, with high negative anomalies noted (except JJA) for all three thermal variables: maximum, minimum and the average daily temperature. Lower wind speeds together with higher SLP and colder air stagnating over Poznań during

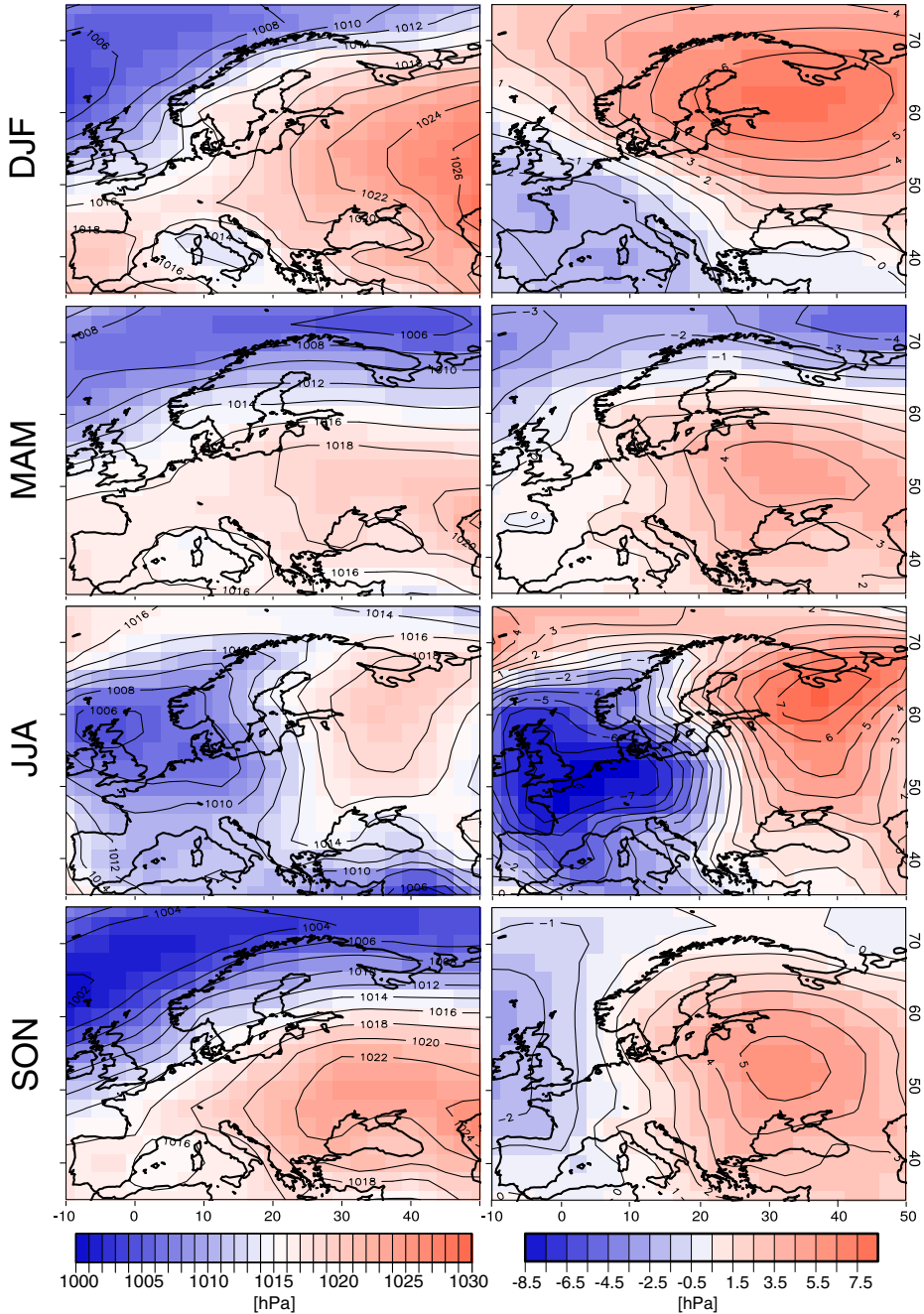


Fig. 7 Mean seasonal pattern and anomalies of SLP for days with exceedance of PM₁₀ threshold value

cold part of the year cause significant decrease of PBL height and worsen atmospheric condition for pollutants dispersion. In case of precipitation this negative anomalies indicate that exceedances occur almost only during dry days regardless of the season.

Although there are some common meteorological anomalies coinciding with high PM_{10} values in Poznań, there are also certain seasonal aspects that need to be discussed here.

6.2 Winter

During DJF season, the most striking features are negative T_{min} (-3.6 °C) and T_{avg} (-3.2 °C) anomalies. This is accompanied by high negative anomalies in the zonal wind speed component (-3.1 m s $^{-1}$), overall wind speed (-1.1 m s $^{-1}$), and positive ($+2.8$ hPa) anomaly of SLP.

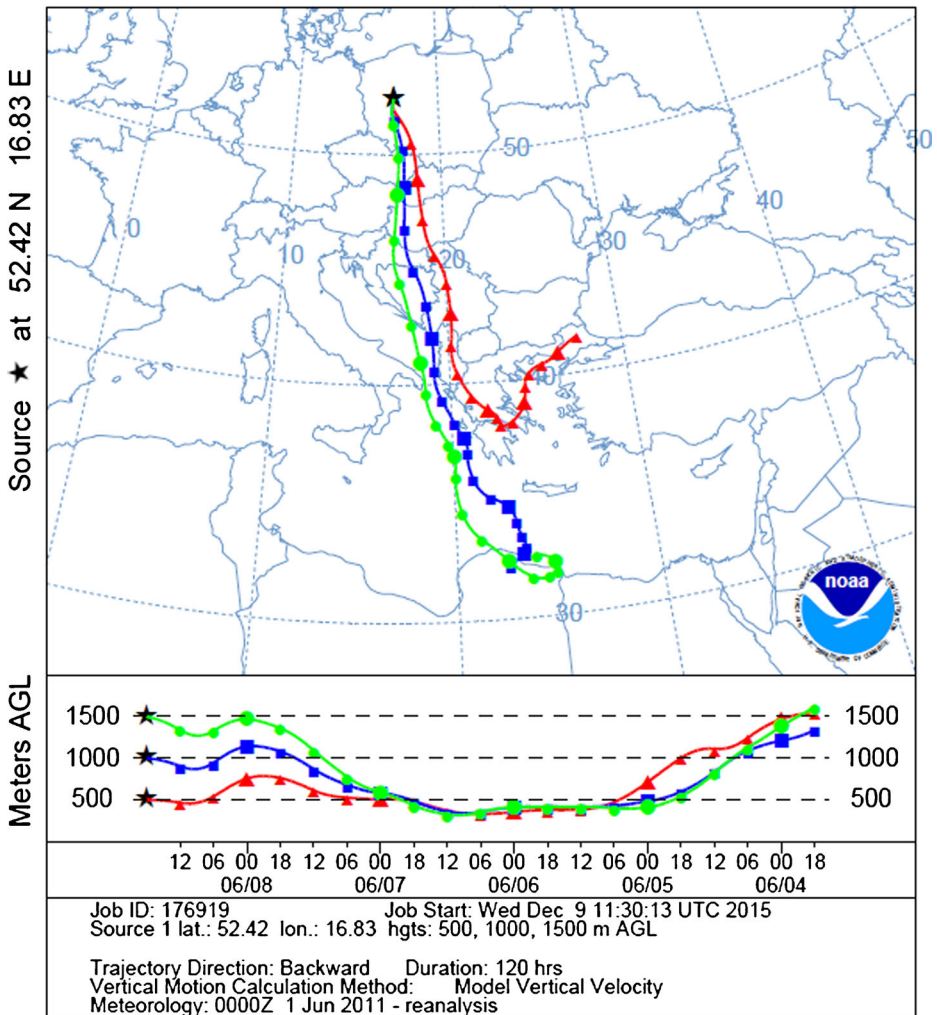


Fig. 8 Backward trajectories ending at 1800 UTC 08 Jun 2011 according to NOAA HYSPLIT model run by NCEP/NCAR reanalysis

In the winter period (DJF), days when the threshold value is exceeded are connected with the occurrence of a high-pressure system with its centre over Ukraine. Pressure anomalies exhibit clear rise over a considerable area of northern and eastern Europe. The values of anomalies along the Finnish-Russian border can exceed +6 hPa (compared to the seasonal average). Such a shape of the SLP field results in the advection of cold air from the eastern sector. This is the cause of large drops in air temperature, particularly during cloudless nights, while at the same time being conducive to temperature inversions near the ground, leading to the weak vertical mixing and shallowing of PBL by 39 % comparing to its average height (Table 4).

6.3 Spring

In spring (MAM), the pattern of anomalies in meteorological variables is somehow similar to the one noted in winter (with the greatest anomaly at $-3.8\text{ }^{\circ}\text{C}$ for T_{\min}). This is true mainly in the case of thermal characteristics. What stands out here is the greater positive anomaly of SLP (+4.0 hPa) and slightly lower value in the case of zonal wind component (-2.3 m s^{-1}). Also, there is a notable increase in meridional wind speed vector component ($+0.5\text{ m s}^{-1}$), pointing to the increased influence of the southern advection.

In spring, thresholds of PM_{10} concentrations are exceeded on days with increased atmospheric pressure over a large area of Europe situated within the range of impact of the high atmospheric pressure ridge from the centre and east of the Black Sea. The anomalies reveal the

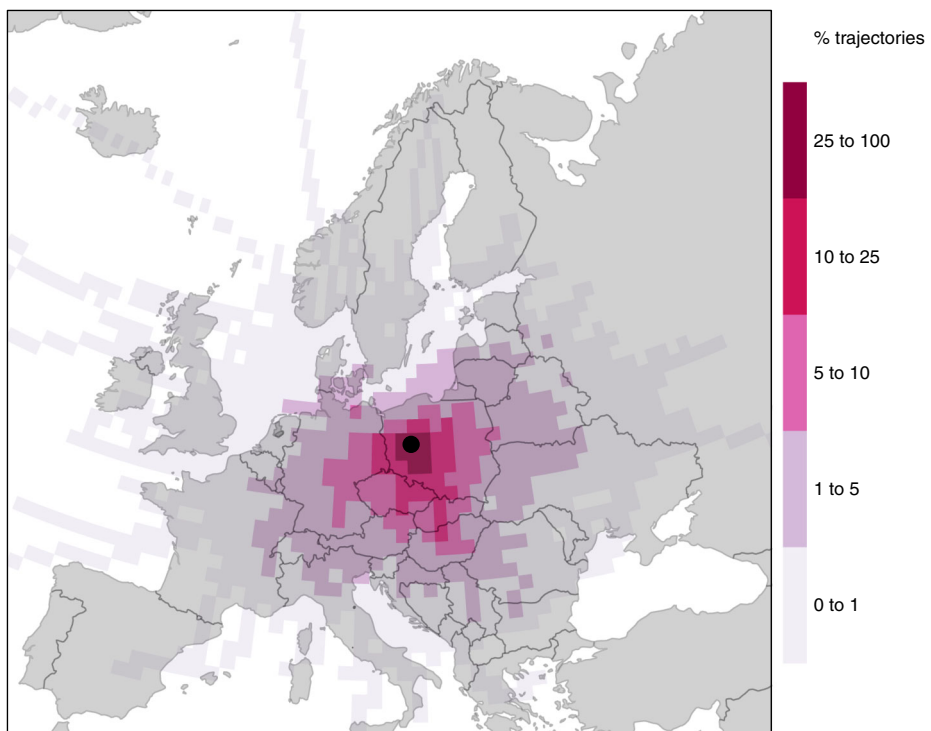


Fig. 9 Frequency of backtrajectories causing exceedance of the PM_{10} legal concentration threshold of $50\text{ }\mu\text{g m}^{-3}$. Analysis based on Hysplit simulations driven by NCEP/NCAR reanalysis

Table 4 Seasonal means and anomalies at Polanka station coinciding with PM₁₀ threshold level exceedances (2005–2013)

Season	Temperature [°C]		Wind speed [m s ⁻¹]			SLP [hPa]			Precipitation [mm]	Low clouds cover [octants]	PBL mean height [m]	
	Max.	Min.	Mean	Max. (incl. Gust)	U	V						
DJF	Anomaly	-2.9	-3.6	-3.2	-1.1	-2.5	-3.1	+0.1	+2.8	-0.8	-0.5	-173
	Mean	2.1	-3.2	-0.3	4.0	6.2	1.0	0.6	1016.5	1.3	5.8	443
MAM	Anomaly	-2.2	-3.8	-2.8	-0.8	-2.3	-2.3	+0.5	+4.0	-1.2	-1.1	-185
	Mean	13.7	3.7	8.9	3.6	7.0	0.6	-0.1	1015.1	1.4	3.8	658
JJA	Anomaly	+5.0	+3.8	+4.8	+1.1	+1.6	-2.7	+3.6	-6.8	-2.0	-2.2	-78
	Mean	24.0	13.6	18.9	3.3	7.1	1.1	-0.1	1014.5	2.3	3.4	781
SON	Anomaly	-2.7	-3.4	-3.1	-1.2	-3.0	-2.2	+0.2	+3.6	-1.0	-0.8	-218
	Mean	13.7	5.4	9.6	3.3	5.7	0.8	0.7	1016.6	1.1	4.3	478

Table 5 Seasonal anomalies of meteorological parameters for days causing cessation of PM₁₀ exceedance at the Polanka station

Season	Temperature [°C]		Wind speed [m s ⁻¹]			SLP [hPa]	Precipitation [mm]	Low clouds cover [octants]	PBL _{min} height [m]		
	Max.	Min.	Mean	Mean	Max. (incl. Gust)					U	V
DJF	+0.1	-0.1	0.1	+0.1	-1.0	+0.5	-0.1	-1.5	+0.7	+0.5	+17
MAM	-1.0	-1.3	-1.1	+0.8	-0.1	-0.5	-0.2	-0.1	-0.4	+0.3	+51
JJA	+6.9	+2.8	+5.0	+0.9	+4.6	+2.8	+0.6	-9.8	-1.3	-0.3	+75
SON	-1.3	-0.6	-0.7	+0.2	-1.3	-0.3	+0.1	+0.6	-0.4	+0.4	+18

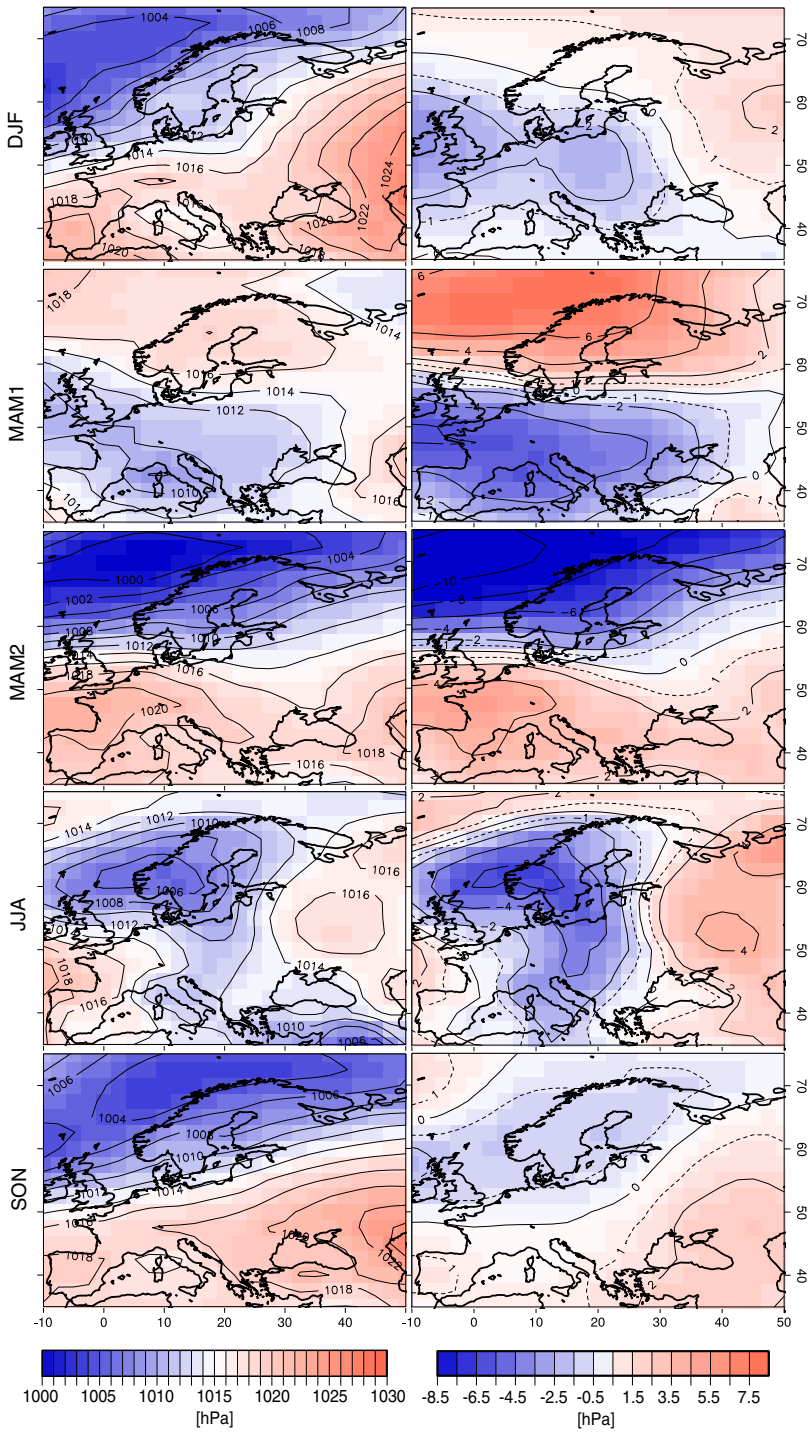


Fig. 10 Mean pattern and anomalies of SLP for the first day after PM₁₀ exceedance episode cessation

occurrence of pressure that is higher than the average value in the analysed season (up to approximately 4 hPa). The effects brought about by such situation are similar to those observed in the winter season. Weak atmospheric dynamics in connection with the absence of conditions conducive to the occurrence of cloudiness are responsible for the radiation loss at night-time together with resulting temperature decrease at the near-surface layer, with the potential for low inversion occurrence (Fig. 7). This also results in lowering of mean daily PBL height on average by 185 m (Table 4).

6.4 Summer

In summer (JJA), there is a substantial shift in the pattern of anomalies when compared with the other seasons. This is the result of the macroscale synoptic situation which is favourable to the development of PM_{10} threshold exceedances (described earlier in section 3.4), i.e. strong advection from the south driving air masses from Africa. This results in high positive anomalies in the case of thermal characteristics, with values of $+5.0\text{ }^{\circ}\text{C}$ (T_{\max}) and $+4.8\text{ }^{\circ}\text{C}$ (T_{avg}). What is also worth mentioning is a substantial decrease in SLP value (-6.8 hPa) and a notable increase in the meridional wind speed vector component ($+3.6\text{ m s}^{-1}$), indicating the prevalence of southern advection.

Situations in which concentrations of PM_{10} are exceeded occur when the territory of Poland is influenced mutually by a high pressure system with the centre to the north-western part of Russia and a low with the centre over northern Scotland. The highest pressure anomalies ($+7\text{ hPa}$) are located over the south of the Kola Peninsula, with the lowest (-6 hPa) over the British Isles. Such a distribution of pressure brings about strong air advection over Poland from a southerly direction. In this case, the high level of dust contamination is not connected with a low emission of impurities into the atmosphere but with an southern advection. An analysis of reverse trajectories shows unequivocally that the air in question originated from the above-mentioned region. Backtrajectories (dated 08.06.2011) point to the advection of dusty air from north-eastern Africa (Fig. 8).

6.5 Autumn

During autumn (SON), meteorological conditions coinciding with PM_{10} level exceedances exhibit strong negative anomaly in wind gusts (-3.0 m s^{-1}) and overall anemological conditions (mean wind speed: -1.2 m s^{-1}). Again, as it was in the case of DJF and MAM, there is a notable positive anomaly in terms of average SLP values (3.6 hPa). This is also reflected in strongest decrease of PBL height among all seasons. In such cases PBL height is lower by 48 % compared to its average height (218 m against 478 m, Table 4).

In autumn, excess concentrations of dust are connected with the SLP pattern similar to that described for spring, but with a clearly higher pressure (anomalies $+3\text{ hPa}$) over the territory of Poland and Belarus (SLP anomalies up to $+5\text{ hPa}$). The high pressure system covers considerable areas of southern Europe from a centre with SLP over 1024 hPa, located east of the Black Sea (Fig. 7).

6.6 Backtrajectories for days with PM_{10} concentrations over $50\text{ }\mu\text{g m}^{-3}$

The abovementioned low-gradient baric situations, observed mainly during winter and often caused by long-lasting episodes of atmospheric blockades or the so-called “European

blocking” (Anstey et al. 2013; Cattiaux et al. 2010), are responsible for environmental conditions being the primary decisive factor in high PM_{10} concentrations observed in Poznań. On the basis of simulations of backtrajectories performed using the HYSPLIT model (Draxler and Rolph 2003) for the entirety of situations in which the threshold value of $50 \mu\text{g m}^{-3}$ has been exceeded, we may state that the concentration of PM_{10} is determined first and foremost by an emission of local origin, primarily anthropogenic, and transported over relatively small distances. The transport of dust originating outside of central Europe, e.g. the natural dust from above Africa as discussed previously, or the volcanic dust from above Iceland connected with the eruption of the Eyjafjallajökull Volcano in 2010, etc., is visible in the analyses performed (Fig. 9) and is reflected in momentary values recorded at both measurement stations. However, the above-mentioned situations are only to a small extent responsible for the frequency of thresholds exceedances. They also constitute more of a side note than an actual threat concerning the possibility that such situations would occur in comparison with the magnitude of the local emission and the obtained distributions of the influx frequency of masses of dusty air transported nearby (Fig. 9).

6.7 Meteorological conditions restoring daily PM_{10} air pollution standards

Similarly, as it was done in chapter 6.1, the analysis presented below comprises the overall shape of meteorological conditions during the first day after cessation of the PM_{10} exceedance event.

In winter, the drop in SLP seems to play the most important role in the interruption of high PM_{10} level ($>50 \mu\text{g m}^{-3}$) events. When analysing the SLP composites of days with PM_{10} threshold exceedance event cessation, it can be noticed that during winter (DJF) the area of Poland stays under the influence of a low pressure system with the centre located north of the British Isles on one side and elevated SLP covering southern and eastern Europe on the other (Fig. 10). The anomalies indicate lower values (of more than 2 hPa) over Poland which suggest the passing of low pressure systems. In general, such SLP pattern results in the fast western advection of warm Atlantic air masses over Poland (Fig. 10, Table 5). The positive anomaly of zonal wind component ($+0.5 \text{ m s}^{-1}$) and the increase in wind speed (in comparison to weak pressure gradient situations favouring high PM_{10} values) induce ventilation as well as an increase in air temperature. This accounts considerably for the decrease in atmospheric pollution concentrations and overall lower emissions from low sources (e.g. home furnaces).

Low values of SLP anomalies during spring (Table 5) do not mean that the SLP itself does not play a role in the elevated concentration breakdown of PM_{10} . It is the result of two separate SLP patterns that are responsible for a swift decrease in PM_{10} concentrations, which have been recognized (MAM1 & MAM2 in Fig. 10). Both result in a very intense zonal flow which is the derivative of high and low pressure centers' location, and thus high horizontal SLP gradient. In case of MAM1, the area of elevated SLP is located over Scandinavia (with anomaly exceeding 6 hPa), while the lower pressure covers vast areas of western and south-western Europe (with the negative anomaly exceeding 3 hPa). Such SLP pattern brings about the eastern advection of continental air. In the second spring pattern (MAM2), the center of high pressure is located over the Biscay Bay (with the anomaly exceeding 3 hPa), whereas the low pressure area resides over Scandinavia and the Norwegian Sea (with negative anomalies exceeding 6 hPa). Such SLP pattern results in the zonal advection of maritime polar air from the west (Fig. 10).

Similarly, as in the case for winter, there is a significant role played by ventilation conditions related to increasing PBL height ($\text{PBL}_{\min} + 51 \text{ m}$), wind speed ($+0.8 \text{ m s}^{-1}$) and

higher air temperatures of about 1.2–2.5 °C in relation to days with high-level PM₁₀ concentrations (see Tables 4 and 5).

The interruption of high PM₁₀ level (>50 µg m⁻³) events in summer is very strongly related to the SLP pattern - SLP anomaly reaches -9.8 hPa (the small sample size should not be overlooked here). In summer, multiple anomalies affecting the interruption of PM₁₀ exceedances seem to occur: high positive anomalies in temperatures (reaching +6.9 °C), latitudinal component of the wind speed (+2.8 ms⁻¹), and maximum wind speed (+4.6 m s⁻¹). The above mentioned variations in the values of meteorological variables can at least be partially attributed to the shape of SLP patterns governing the airflow over the research area.

The cessation of high PM₁₀ concentrations in summer is the result of the advection from the western sector which is connected with low pressure system over southern Scandinavia (Fig. 10), extending to the south and thus directly influencing the research area. While comparing the SLP pattern and its anomalies, one may notice an eastern shift in the location of low and high pressure systems in comparison with the pattern responsible for elevated PM₁₀ concentrations (Fig. 10). This is reflected by an opposite sign of anomalies for zonal wind flow and significantly smaller meridional components (Table 5).

The break in the high PM₁₀ concentrations in autumn is the result of SLP pattern similar to the winter season (with a slight difference in the flow direction over Poland, and a north-eastern shift in the location of the low pressure center). A fast transition of air masses over Poland from a WSW direction is the result of the presence of lower pressure over the Norwegian Sea (with negative anomaly over 1 hPa) and well developed higher pressure over south-eastern Europe (> 2 hPa anomaly) (Fig. 10). Similarly, as in the case of both: winter and spring, there are also notably higher air temperatures of about 1.4–2.8 °C in comparison with days with high-level PM₁₀ concentration (see Tables 4 and 5).

7 Summary and conclusions

PM₁₀ variability is characterized by a very complex system of natural and anthropogenic elements that include human activity and those related to it: emission strength, transport of pollutants, coagulation, wet and dry deposition, particle transformation, other physical and chemical processes (Zhang et al. 2012); altogether, these build a highly non-linear set of interactions. Part of those connections might be observed in the analysis carried out in the city of Poznań, which is a typical example of a fairly large central European city that needs to face up to the problem of high PM₁₀ concentration (European Environment Agency 2015).

As shown in the climatological analysis, there is a clear reaction of PM₁₀ levels to different types of human activity on a daily cycle, especially those related to morning and afternoon traffic rush hours or heating needs, so the daily maxima (ca. 40 µg m⁻³) are usually observed around midnight, while minima (ca. 25 µg m⁻³) occur 1–2 h after the daily maximum air temperature (around 15 UTC). In general, the atmospheric conditions in Poznań are found to be responsible for a great number of situations with air quality problems. The PM₁₀ daily amplitude of 15 µg m⁻³ is not only a result of human activity, emission strength, and pollutant transport, but also reflects the diurnal cycle of mixing-layer height (Oke 1995). This regularity of the lowest values (<30 µg m⁻³) occurring between 12 and 19 UTC is repeated on a daily basis, so in the authors' opinion, those hours should be promoted, e.g. for outdoor activities. As the effect of smaller traffic and industrial activity, the smallest PM₁₀ values are observed on

Sundays and Mondays ($30\text{--}32 \mu\text{g m}^{-3}$), with the highest ones on Tuesdays and Wednesdays ($32\text{--}36 \mu\text{g m}^{-3}$). This is because of a mid-term inertia in PM_{10} that propagates the instantaneous emission intensity to the following days. On a seasonal time scale, PM_{10} are negatively correlated with the annual cycle of air temperature. A maximum (monthly average) concentration of over $50 \mu\text{g m}^{-3}$ is observed in February, and a minimum (around $20 \mu\text{g m}^{-3}$) in June and July.

From the standpoint of applicable environmental standards, the greatest challenges posed to air quality management services may be the annual and daily concentrations of PM_{10} . Those values (i.e. number of days with the exceedance of the daily mean threshold value of $50 \mu\text{g m}^{-3}$) are smaller than in some Mediterranean parts of Europe where it may even reach over 200 days per year (Karaca et al. 2009). However, as stated in Fig. 5, the problem varies from year to year. On average, there are approximately 71.3 days per year anywhere in Poznań that exceed the threshold value against the 35 days demanded by the regulations. Almost half of those situations occur in winter, while 83.7 % of all cases are observed as continuous episodes of a few days, with the longest recorded one persisting for 22 days. The longest episodes are observed in winter, mainly during atmospheric blockades (Anstey et al. 2013; Cattiaux et al. 2010) when the concentration level of PM_{10} is determined by an emission of local origin as well as weak ventilation conditions and lowering PBL height (Nidzgorska-Lencewicz and Czarnańska 2015; Lewandowska and Falkowska 2013). This situation favours a very high instantaneous PM_{10} concentration, even above $200 \mu\text{g m}^{-3}$ which occurred in the Polanka station 4 times, and always with the wind speed between 1.0–2.5 m/s (there must be a positive wind speed to preserve mixing conditions), in the center of the anticyclone, with PBL height below 50 m, strong thermal inversions and temperatures below zero.

This suggests the high influence of atmospheric conditions on PM_{10} levels. However, the atmospheric conditions, especially during non-dynamic synoptic episodes, conserve the previous state of air pollutions. Therefore, high values of PM_{10} very often result from a previous state of the atmosphere that is confirmed by the autocorrelation signal, which depending on the season can reach up to 0.70 (1-day lag Pearson correlation coefficient in autumn).

PM_{10} concentration in Poznań is to a large extent responsive to changes in the PBL height especially in winter and autumn ($r = -0.65$, SON). For the meteorological parameters (except during summer, when a number of cases cause the disordered results), correlation values that exceed ± 0.2 are observed for the average and minimum air temperature (-0.56 , DJF), the maximum temperature (-0.51 , DJF), sea level pressure (0.30, SON), average total cloudiness (-0.33 , DJF and JJA), average low cloudiness (-0.41 , JJA), wind speed (-0.52 , DJF), and maximum daily wind (-0.44 , SON). However, it must be kept in mind that above mentioned meteorological features and their relationship might be cross-correlated and thus require additional statistical preprocessing e.g. for the needs of statistical model building.

It has been observed that in all seasons (except summer), dustiness standards are exceeded when the weather is accompanied by a high pressure system, with the advection of cold from the eastern sector and hence the increased potential for the occurrence of low air temperature and inversions following the radiation of heat at night-time. In such instances, we observe the increased emission of contaminants, particularly from household furnaces, with a simultaneously weak horizontal atmospheric pressure gradient that results in the lack of or only slight ventilation of cities that is confirmed by negative anomalies of PBL height. Only in summer the increased concentration of PM_{10} is brought about by the inflow of dusty air from the south, which is the result of long-range atmospheric transport connected with maintenance of a favourable distribution of the pressure field over Europe and the Mediterranean Basin (Fig. 9).

To conclude, one might state that the cessation of high PM₁₀ concentration events from autumn until spring coincides with the fast zonal flow from the west. Only in spring one can observe a higher influence of eastern advections, whereas during summer the SLP pattern associated with higher PM₁₀ concentrations shifts eastwards so that there is an advection of clean air from the Atlantic Ocean over Poland. All aforementioned SLP patterns trigger a fast air mass advection, and thus ventilation of the research area.

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