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ORIGINAL PAPER

SULFUR DIOXIDE CONCENTRATIONS WITHIN THE CITY OF POZNAŃ (MID-WEST POLAND) FROM 2005 TO 2016 – THE TEMPORAL STRUCTURE AND DEPENDENCE ON METEOROLOGICAL CONDITIONS*

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Abstract

Air quality within cities is determined not only by the distribution of pollutants but also by the changing meteorological conditions that elevate or reduce the concentration of a given pollutant and induce physicochemical transformations. The aim of this work was to determine the variability and time distribution of sulfur dioxide (SO_2) concentration in the urban landscape of Poznań. To achieve this goal, hourly SO_2 concentration data from the automatic central city weather station Poznań-Dąbrowskiego for the period 2005-2016 were compared against the respective hourly meteorological data: air temperature, relative air humidity, atmospheric pressure, wind speed and direction. Relationships between the concentration of SO_2 and the various meteorological elements or a set of meteorological conditions across the multi-annual period were established using a Pearson correlation coefficient and multiple element regression analysis. Over the period 2005-2016, SO_2 concentration distribution in Poznań was characterized by a marked seasonal and monthly variation, with SO_2 levels more than 3 times higher in winter than in summer. The highest average concentrations of SO_2, > 10.5 μg m^{-3}, were recorded in the winters during winds from the easterly quarter: E, NE, SE. The levels of SO_2 significantly depended on meteorological conditions, with positive correlations with atmospheric pressure in winter and a general negative correlation with air temperature, relative humidity and wind speed. For the multi-annual period 2005 to 2016, the annual average concentration of SO_2 ranged from 6.5 to 22.7 ug m^{-3} during the easterly winter winds, air temp. ranged from 7.9°C in 2010 to 1.2°C in 2005, relative air humidity ranged from 82.9% in 2011 to 95.8% in 2009, atmospheric pressure varied from 1001.0 hPa in 2009 to 1022.2 hPa in 2005, and wind speed

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varied from 1.1 m s^{-1} in 2013 to 2.0 m s^{-1} in 2016. On the basis of the research it can be observed that the variability of SO_2 concentrations in Poznań is affected by the heating season and the location of the city's heat and power plants.

Keywords: aerosanitary conditions, weather-SO_2 dependence, meteorological elements, air pollution.

INTRODUCTION

Sulfur dioxide (SO_2) is a colorless gas with a sharp and stifling odor which can strongly irritate the respiratory tract. It is absorbed into the human body through the nasal mucosa and upper respiratory tract, and then penetrates into the blood and further into the entire organism (WHO 2005, Khaniabadi et al. 2017*ab*). SO_2 is accumulated in the walls of the trachea as well as in the liver, brain and lymph nodes. In high concentrations it can cause aggravation such as conjunctivitis and skin disease, induce severe upper airway catarrh, and even shorten human life (Tainio 2015, Chen et al. 2017, Khaniabadi et al. 2017*a*, Renzi et al. 2017, Zhu et al. 2017). Elevated concentrations of SO_2 adversely affect various elements of the environment such as the soil, water and plants, including plant communities (Adamska 2011, Lisowska 2011, Rydval, Wilson 2012, Bęś, Baciak 2015, Klikocka et al. 2015, Vacek et al. 2015) and avifauna (Muyemeki et al. 2017).

SO_2 is formed mostly by the combustion of fossil fuels containing sulfur additives or its compounds, such as in coal-fired power plants and industrial plants, local boiler houses, individual boilers, and the internal combustion engines of vehicles (Hand et al. 2012, Khattak et al. 2014, Basic report 2015, Kijewska et al. 2016).

In the air, SO_2 is oxidized to SO_3 and in combination with water vapor creates sulfuric acid, the main component of acid rain (Talbot et al. 2007). Sulfur dioxide contamination may involve large areas as a result of transport within air masses over long distances (Černikovský et al. 2016). SO_2 is also a component of smog in urban agglomerations, aggravated by windless weather and no precipitation (Walczewski 2000). Air temperatures below 0°C also favor high levels of SO_2 in the atmosphere, when households intensify fuel combustion for heating purposes. Such meteorological conditions occur in winter during high atmospheric pressure, with all the aforementioned conditions at the same time (Widawski 2015).

In Poland, the maximum permissible level of atmospheric SO_2 for one hour is 350 μg m^{-3} and an average daily concentration of 125 μg m^{-3}, which may not be exceeded more than 3 times a year. The permissible level for plant protection cannot exceed 20 μg m^{-3} annually. According to the World Health Organization (WHO), the average daily concentration of SO_2 should not exceed 20 μg m^{-3} (WHO 2005). Estimates show that approx. 45% of urban residents in the EU are exposed to levels exceeding the WHO recommended value, and about 1% of residents are exposed to levels exceeding 125 μg m^{-3}.

In recent years Poland has had the fourth highest levels of atmospheric SO_2, following Bulgaria, Romania and Slovakia (Guerreiro et al. 2014, EEA Report 2016). Therefore, the aim of this study was to assess the variability of SO_2 concentration in an urban area depending on the wind direction and other weather conditions, based on meteorological and pollution data from Poznań, a city in mid-western Poland with nearly 550 thousand inhabitants.

MATERIAL AND METHODS

This work is based on hourly data on the concentration of sulfur dioxide (SO_2, μg m^{-3}) from January to December in the period 2005-2016, compared against hourly meteorological data from the same period: air temperature (Ta,°C), relative humidity (Rh, %), atmospheric pressure (Pa, hPa), and wind velocity (V, m s^{-1}) and direction (Wd, 360°), collected from the automatic weather station Poznań-Dąbrowskiego (λ = 16°52′52″ E, φ = 52°25′08″ N, *hs* = 89 m a.s.l.) belonging to the Provincial Inspectorate for Environmental Protection (Figure 1). The station is located in the central part of Poznań, in the Botanical Garden of the Adam Mickiewicz University. The monitoring of air quality at the station is based on analyzers and automatic sensors that constantly measure the concentration of pollutants (including SO_2) and meteorological elements; Ta, Rh, Pa, V and Wd. The measurements were taken at a height of 2-3 m above ground level, except for wind characteristics whose sensors were placed at approximately 10 m AGL. The results of

Fig. 1. Location of the National Environmental Monitoring Station in Poznań (■)

measurements are presented online in real time on the website of the Environmental Protection Inspectorate.

The variability in SO_2 concentration was also characterized for various time intervals: monthly, seasonal (winter – December to February, spring – March to May, summer – June to August, autumn – September to November) and annually, both for individual years from 2005 to 2016 as well as for the entire period 2005-2016. The SO_2 level was also compared with wind directions based on the wind rose, with average values in 2005-2016 and the incidence of low and high SO_2 levels, i.e. < 1 and > 20 μg m^{-3}, determined on the basis of the approx. 20^{th} and 97^{th} percentiles of the entire set of data, numbering approx. 9.5 thousand measurements in total.

The relationship between average daily SO_2 concentration and the various meteorological elements or the set of meteorological conditions in the period 2005-2016 was determined in four analyzed seasons by means of Pearson correlation coefficient and multiple regression analysis. The direction and strength of the effects of the analyzed relationships were estimated using the correlation coefficient, while the fit of the empirical data to the regression function was determined on the basis of a Snedecor *F*-test and the adjusted coefficient of determination (R^2_{adj}, %). The effect of each individual meteorological element in the variability of SO_2 level in the air was described by a Student's *t*-test and a partial correlation coefficient. For a more accurate identification of relationships between weather and the level of SO_2, an analysis was carried out in individual months using daily averages, and also an analysis of the wind direction in winter – the season characterized by the highest average SO_2 concentrations.

Before statistical analysis, the dependent variables were transformed according to the formula $f(SO_2)=\sqrt{(SO_2)}$, where SO_2 denotes the concentration of sulfur dioxide. The transformation of the dependent variable (concentration of SO_2) in regression equations is performed by other scientists – Giannitrapani et al. (2007).

RESULTS

Temporal distribution of sulfur dioxide concentration

In the period 2005-2016 the concentration of SO_2 in Poznań averaged 4.5 μg m^{-3}, ranging from an average of 2.5 μg m^{-3} in summer to 7.8 μg m^{-3} in winter (Figure 2*a*). Even more clearly, the multi-annual seasonal variation of the analyzed air pollutant could be seen in the monthly data. The highest pollution with SO_2, on average 8.5 μg m^{-3}, was recorded in January, then in February (7.7 μg m^3), with the lowest in August (2.4 μg m^{-3}). The average monthly level of SO_2 in the air varied even more than the annual average in the entire period, ranging from 0.8 μg m^{-3} in July 2011 to 18.0 μg m^{-3}

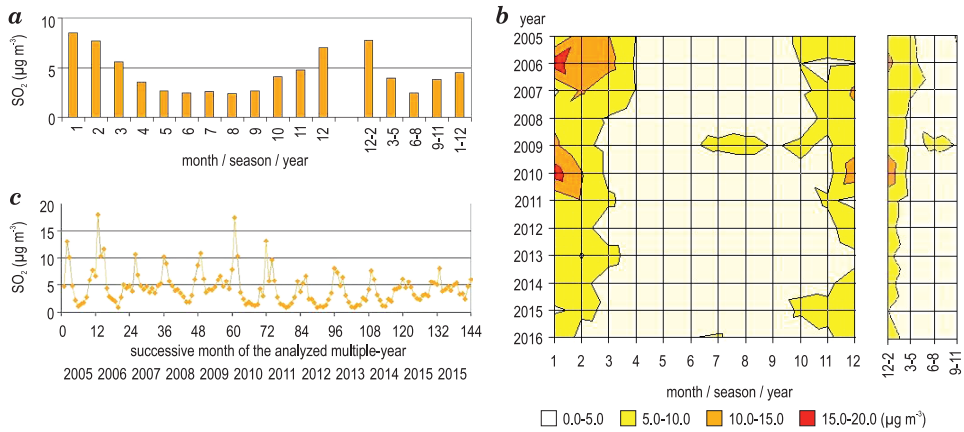

Fig. 2. Variations in the level of SO_2 concentration in the multi-annual period 2005-2016 (*a*) and in the individual years (*b*, *c*) over various time intervals

in January 2006 (Figure 2*b*). An average monthly level of SO_2 above 10.0 μg m^{-3} was recorded in 11 of the 144 analyzed months (12 years x 12 months): in February-March 2005, in January-March 2006, in February and December 2007, in January 2009, in January-February 2010, and in December 2010, while a level above15.0 μg m^{-3} was only found in 2 months: January 2006 and January 2010 (Figure 2*c*). Of the 48 analyzed seasonal periods (12 years x 4 seasons), only two had an average concentration of SO_2 above 10.0 μg m^{-3}; winter 2006 and winter 2010.

The concentration of sulfur dioxide depending on the wind direction

In the period 2005-2016, high SO_2 concentrations, above 10 μg m^{-3}, were recorded in the winters during winds from the easterly quarter; E (14.3 μg m^{-3}) then NE (12.1 μg m^{-3}) and SE (10.5 μg m^{-3}), which directly relates to a group of large SO_2 emitters east of the city; the coal-fired power and heating plants (Figure 3).

In summer, the concentration of SO_2 was more than 2 to 4 times lower than in winter, and the level also depended on the wind direction; from 1.6 μg m^{-3} for a NW wind to 3.6 μg m^{-3} for a SE wind. The lowest SO_2 levels, under 1 μg m^3, were most frequently recorded during SW (39%) and W (23%) winds in winter, around 18% and 28% in spring, 20% and 21% in summer, and 24% and 20% in autumn. The highest SO_2 levels, above 20 μg m^{-3}, were most frequently recorded during E (50%) and SE (22%) winds in winter, around 32% and 26% in spring, 24% and 48% in summer and 45% and 30% in autumn. The highest average annual SO_2 levels, i.e. > 20 μg m^{-3}, were recorded in 2005, 2006 and 2010 during NE and E winds (Figure 4). Distinctly lower annual levels were observed for SW, W and N winds, ranging from 2.5 μg m^{-3} for W winds (2012) to 9.9 μg m^{-3} for SW winds (2010).

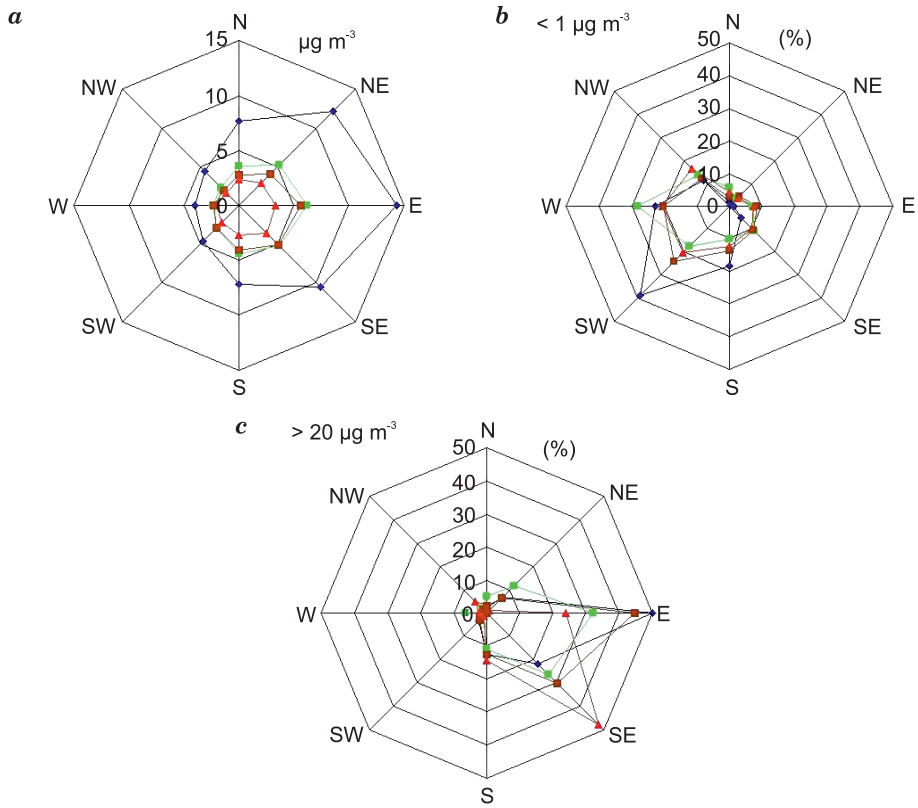

Fig. 3. Wind rose, characterizing the average concentration of SO_2 (*a*) and the incidence of SO_2 concentration below 1 μg m^{-3} (*b*) and above 20 μg m^{-3} (*c*). Years 2005-2016

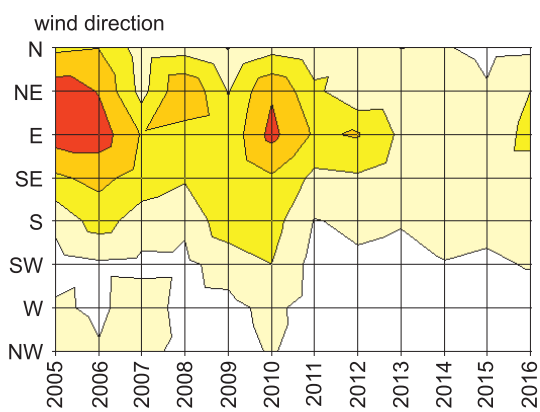

Fig. 4. Distribution of the average annual SO_2 concentration in the years of the analyzed multi-annual period by wind direction

Frequency of individual sulfur dioxide concentration ranges

The concentration of SO_2 across the period 2005-2016 was most often below 5 μg m^3 (Figure 5*a*), being approx. 50% of the measurements in winter,

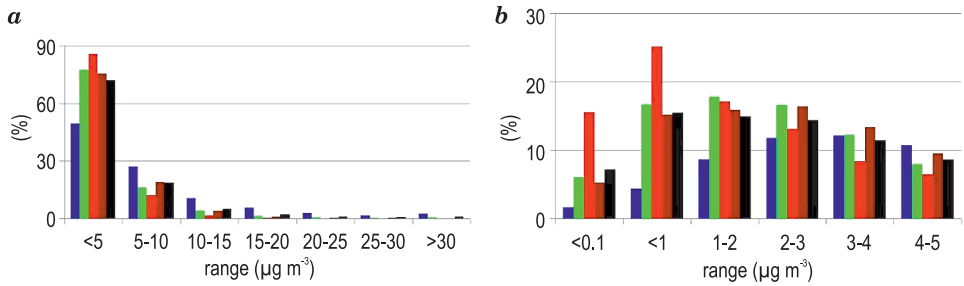

Fig. 5. Frequencies of hourly SO_2 concentration ranges. Years 2005-2016

approx. 86% in summer, and slightly more often in spring (77.1%) than in autumn (75.5%). The range 510 μg m^{-3} was most often recorded in winter (about 27%), then autumn (about 19%), and the least often in summer (approx. 12% of measurements). Concentrations of SO_2 from 10 to > 30 μg m^{-3} were recorded least frequently in summer and autumn, and most often in winter. For example, in the ranges 1015 and > 30 μg m^{-3}, the concentrations were recorded with a frequency of approx. 11 and 3% in winter, approx. 4 and 1% in spring, ca. 4 and 0.1% in autumn, and ca. 2 and 0.1% in summer. Due to the large variability in concentrations of monitored SO_2 levels below 5 μg m^{-3}, an additional analysis was performed, which demonstrated that the intervals <1, 12, 23, 34, 45 μg m^{-3} were recorded most frequently respectively in summer (ca. 25%), spring (ca. 18%), spring (ca. 13%), autumn (ca. 13%), and winter (ok. 11%) – Figure 5*b*. Concentrations of SO_2 < 0.1 μg m^{-3} occurred with an annual frequency of approx. 7%; approx. 16% in summer and approx. 2% in winter.

The distribution of SO_2 levels in the air depended not only on the season of the year (Figure 5*ab*), but also on the time of day, both in the entire multi-annual period and in the individual years (Figure 6). Over the entire period 2005-2016, concentrations below 5 μg m^{-3} were most often recorded in summer

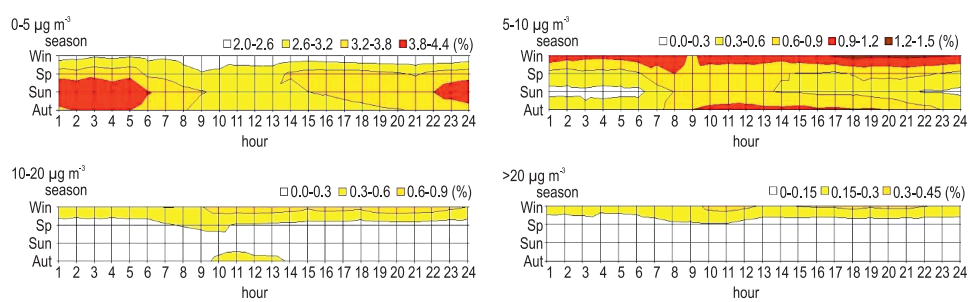

Fig. 6. Prevalence of SO_2 concentration ranges by seasons and hours. Years 2005-2016

from 10 pm to 6 am, in autumn from 2 am to 5 am, and least often in winter throughout the entire day. The range 510 μg m^{-3} was most often detected in winter, between 4 pm and 11 pm, and least often in summer, between 10 pm and 6 am. The ranges 1020 and > 20 μg m^{-3} were recorded most often in winter, from 10 am to 11 pm and from 10 am to 10 pm, respectively. In the individual years of the 2005-2016 period, the variability of air SO_2 levels was as pronounced as for the entire multi-annual period (Figure 7). The range of

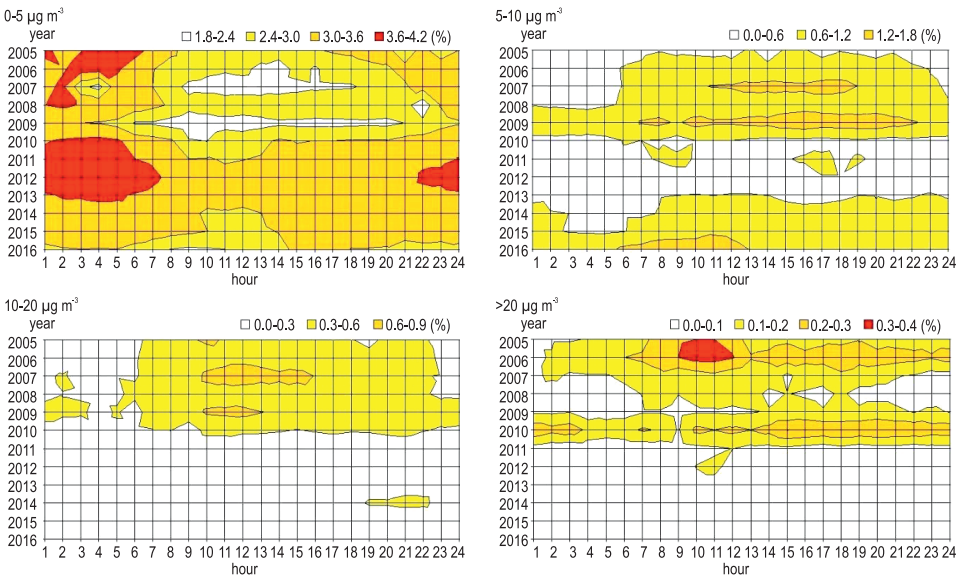

Fig. 7. The incidence of concentration ranges of SO_2 by the years of the analyzed multi-annual period and hours

05 μg m^{-3} was most frequently detected in 2005-2006 and 2010-2013 from 1 am to 6 am, and in 2012 between 10 pm and midnight. It was least frequently detected in 2007 and 2009 from 9 am to 6 pm. The range 510 μg m^{-3} was most frequently detected in 2005-2010 and 2014-2016, between 6 am and midnight. In turn, the ranges 1020 and > 20 μg m^{-3}, were most frequently detected in the first years of the analyzed multi-annual period from 2005 to 2010. The SO_2 range of 1020 μg m^{-3} was most frequently recorded in 2007 from 10 am to 3 pm, and in 2009 between 10 am and 1 pm. The range > 20 μg m^{-3} in 2005 from 10 am to 11 am, and in 2006 between 9 am and 12 am.

Relationship between sulfur dioxide concentration and meteorological conditions, and their course over subsequent years

The air temperature (Ta) over the period 200-52016 significantly positively affected the level of the average daily air concentration of SO_2 in all analyzed seasons. The relationship was negative in winter, spring and autumn, and positive in summer (Table 1). The closest relationship with

Table 1

Correlation between daily SO_2 concentration and meteorological elements. Years 2005-2016

Element	Season of the year			
	winter	spring	summer	autumn
	n = 1051	n = 1080	n = 1080	n = 948
Ta (°C)	-0.54***	-0.25***	0.18***	-0.32***
Rh (%)	-0.19***	-0.27***	-0.24***	-0.12***
Pa (hPa)	0.18***	n.s.	n.s.	n.s.
V (m s^{-1})	-0.40***	-0.22***	-0.22***	-0.13***

Ta – air temperature (°C), Rh – air relative humidity (%), Pa – atmospheric pressure (hPa), V – wind speed (m s^{-1}), n – number of samples, *** significant at $P < 0.01$, n.s. – non significant at $P < 0.1$

Ta was observed in winter (r = 0.54, $p < 0.01$). Relative humidity (Rh) and wind velocity (V) had a significant negative effect on sulfur dioxide levels in all seasons. The correlation coefficient for $RhSO_2$ ranged from 0.12 in autumn ($p < 0.01$) to 0.27 in spring ($p < 0.01$), and for VSO_2 from 0.13 in autumn ($p < 0.01$) to 0.40 in winter ($p < 0.01$). Atmospheric pressure (Pa) significantly positively influenced SO_2 level in winter (r = 0.18, $p < 0.01$).

In the multi-annual period 2005-2016, the impact of meteorological conditions on the level of SO_2 in the air was also estimated based on hourly measurements for individual months (Figure 8). The strongest positive correlation ($r > 0.4$) for Ta-SO_2 was shown for May from 10 am to 6 pm, and for

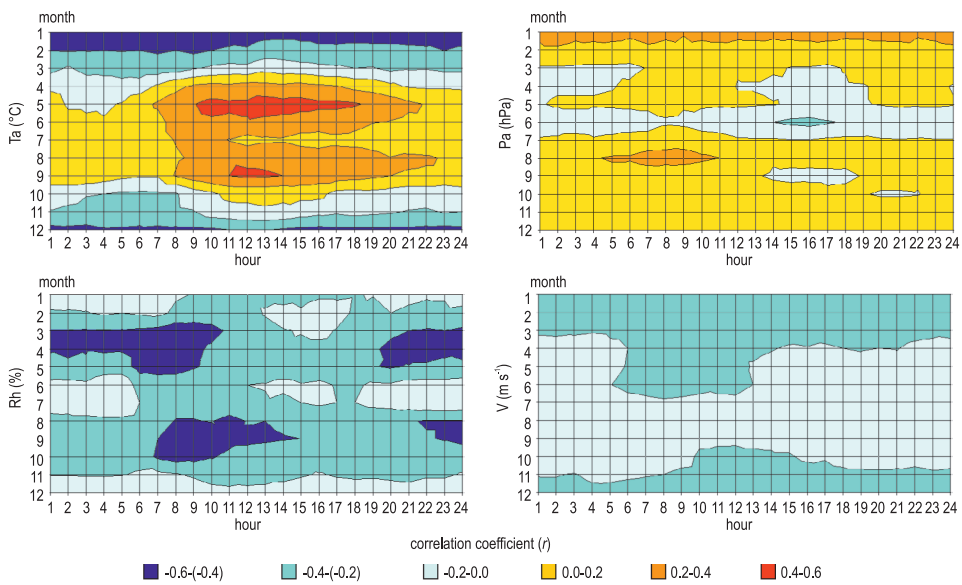

Fig. 8. Monthly distribution of the correlations between hourly SO_2 concentration and meteorological elements. Years 2005-2016

September between 11 am and 2 pm, with the strongest negative correlation ($r < 0.4$) for January throughout the entire day, for February from 11 pm to 10 am, and December from 2 pm to 10 am. The levels of SO_2 also depended on Rh, as previously stated on the basis of daily mean data (Table 1), with the strongest correlation for this compound statistically confirmed for March and April between 9 pm and 9 am, May from 6 am to 9 am, and for the period August-September from 8 am to 1 pm, and 11 pm to 0 am, and for October between 7 am and 10 am. Atmospheric pressure showed the strongest positive effect ($r > 0.2$) on SO_2 levels in January at all hours of the day, and in August between 5 am and 10 am. A negative impact of air pressure on SO_2 was observed in June at all hours of the day, in July from 2 pm to 4 pm, and from 9 pm to midnight, and also in March-May – mainly between 1 am and 5 am, and from 3 pm to 6 pm, as well as in September between 2 pm and 6 pm, and October from 8 pm to 10 pm. Wind velocity in all months and the analyzed hours had a negative effect on the level of SO_2 in the air, with the strongest influence observed in January-March, November-December, April-June from 6 am to 1 pm, and in October from 10 am to 3 pm.

The multiple regression equations showed that the concentration of SO_2 depended significantly on the set of meteorological conditions: Ta, Rh, Pa and V, from about 9% in summer ($F = 36.6$) to even about 38% in winter ($F = 216.8$) – Table 2. In winter, the concentration of SO_2 was most strongly determined by the air temperature, for which the determined partial correlation coefficient (*rp*) was 0.42. In spring it was mostly determined by Ta (*rp* = -0.47) and Rh (*rp* = -0.45), in summer by Rh (*rp* = -0.23), and in autumn by Ta (*rp* = -0.55). The partial correlation coefficient describing the effect of wind velocity on the level of air SO_2 ranged from 0.201 in summer to 0.28 in winter.

Table 2

The combined impact of weather conditions on the average SO_2 daily concentrations in the analyzed seasons. Years 2005-2016

Season of the year	Coefficients of partial correlation of multiple regression				*n*	Evaluation of the equation's fit	
	Ta (°C)	Rh (%)	Pa (hPa)	V (m s^{-1})		$R^2_{adj.}$	*F*
Winter	-0.42 (-16.4)#	-0.207 (-8.3)		-0.28 (-10.6)	1051	38.1	216.8
Spring	-0.47 (-16.5)	-0.45 (-15.2)	-0.19 (-6.6)	-0.27 (-9.9)	1088	28.5	109.3
Summer		-0.23 (-7.4)	-0.086 (-2.8)	-0.201 (-6.6)	1080	9.1	36.6
Autumn	-0.55 (-16.4)	-0.404 (-12.1)		-0.23 (-7.5)	948	24.1	76.3

In brackets there are values of *t*-Student's test at significance level $P < 0.01$, R^2_{adj} – adjusted determination coefficient (%), *F* – *F*-Snedecor test. Other explanations, see Table 1.

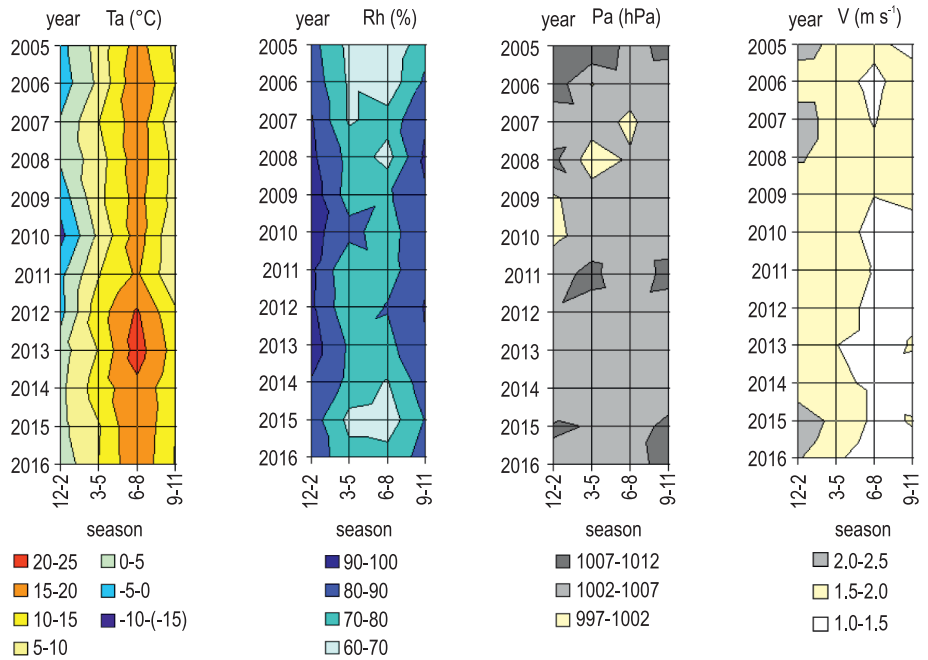

Fig. 9. Distribution of meteorological elements by seasons and in subsequent years of the analyzed period 2005-2016

In the study period 2005-2016, the air temperature ranged from 6.6°C in winter (2010), when the highest average SO_2 level was recorded (Figure 2), to 22.4°C in summer (2013) – Figure 9. In five of the years, 2005, 2006, 2008, 2013 and 2015, Ta in spring was lower than in the autumn, by 1.8, 4.1, 0.4, 2.3 and 0.4°C. The relative humidity of the air varied from about 62% in the summer of 2005 to about 96% in the winter of 2009. The lowest Rh, 60%70%, occurred in spring and summer in the years 2005, 2006 and 2015, while the highest, at over 90%, in the winter of 2008 and the autumn of 2012. The changes in atmospheric pressure over 2005-2016 were definitely less regular than Ta and Rh; the highest levels, > 1007 hPa, were noted in 2005 (winter, spring and autumn), in 2011 (in spring and autumn) and in 2015 (in winter and autumn). Wind velocity ranged from 1.0 to 1.5 m s^{-1}, mainly in summer and autumn in 20102016, to 2.02.5 m s^{-1} in the winters of 2005, 2007, 2008, 2015 and 2016.

The correlation between the concentration of sulfur dioxide in winter and meteorological elements in relation to wind direction

An assessment of the weather to SO_2 correlation was also made depending on a wind direction, but only for winter, the season with the strongest correlation (Table 3). The correlation coefficient calculated for the pair Ta-SO_2 ranged from 0.52 ($P < 0.01$) for E wind to 0.22 ($P < 0.01$) for N wind.

Table 3

The correlation between the hourly winter concentrations of SO_2 and meteorological elements depending on the wind direction. Years 2005-2016

Element	Wind direction								
	N	NE	E	SE	S	SW	W	NW	C
	n = 605	n = 700	n = 3882	n = 3731	n = 4437	n = 5441	n = 3542	n = 1212	n = 559
Ta (°C)	-0.22***	-0.39***	-0.52***	-0.41***	-0.35***	-0.30***	-0.31***	-0.37***	-0.26***
Rh (%)	-0.19***	-0.16***	-0.25***	-0.17***	-0.17***	-0.04***	-0.04**	-0.06**	-0.09**
Pa (hPa)	n.s.	n.s.	0.21***	0.21***	0.17***	0.14***	0.22***	0.18***	-0.17***
V (m s^{-1})	n.s.	n.s.	n.s.	-0.17***	-0.21***	-0.31***	-0.28***	-0.39***	n.s.

C – lull, ** significant with $P < 0.05$. Other explanations, see Tables 1 and 2.

The effect of Rh on the level of SO_2 in the air was negative; the strongest was found for the E wind (r = -0.25, $P < 0.01$), i.e. just as in the case of Ta. Atmospheric pressure had a significant positive effect on SO_2 levels; the strongest for W (r = 0.22, $P < 0.01$), E (r = 0.21, $P < 0.01$) and then SE winds (r = 0.21, $P < 0.01$). Wind velocity, as well as Ta and Rh, had a negative effect, most strongly for western winds: NW (r = -0.39, $P < 0.01$), SW (r = -0.31, $P < 0.01$), and W (r = -0.28, $P < 0.01$). During windless weather, the level of SO_2 depended significantly negatively on Ta (r = -0.26, $P < 0.01$), Rh (r = -0.09, $P < 0.05$), and Pa (r = -0.17, $P < 0.01$).

Depending on the direction of air inflow to the air quality monitoring station in Poznań, the degree of the impact of meteorological conditions on SO_2 levels varied and ranged from approx. 10% for northerly winds to approx. 30% for easterly winds (Table 4). All models of multiple regression took into account the air temperature and relative humidity; their influence was determined by means of the partial correlation coefficient and was significant, ranging from 0.49 for E winds to 0.22 for N winds in the case of Ta, and from 0.31 for S winds to 0.09 for W winds in the case of Rh. Among the meteorological conditions, the effect of Pa on the levels of SO_2 Pa was ambiguous; negative for N and NE winds, and positive for S and W winds. Wind velocity had a significant impact on the analyzed concentration; the strongest for NW wind (rp = 0.34), and then for SW wind (rp = 0.27). During windless weather, air levels of SO_2 depended on Ta (rp = 0.30) and Pa (rp = 0.24) in ca. 27%.

Variability of the distribution of meteorological elements in winter depending on wind directions

In the winters in the period 2005-2016, the warmest air flowed into Poznań from SW and S, on average with a temp. of 1.7 and 1.4°C, respectively. The coolest winds were from NE, E and N (average temp. of 4.0, 3.5 and 3.3°C (Figure 10). The relative humidity of the air was on average around 90% and fluctuated from about 88% for the air flowing from NE

Table 4

Assessment of the combined impact of meteorological conditions on the size of the hourly winter concentration of SO_2 depending on wind direction. Years 2005-2016

Wind direction	Coefficients of partial correlation of multiple regression				*n*	Evaluation of the equation's fit	
	Ta (°C)	Rh (%)	Pa (hPa)	V (m s^{-1})		$R^2_{pop.}$	*F*
N	-0.22 (-5.6)*	-0.25 (-5.9)	-0.11 (-2.7)	-0.11 (-2.4)	605	10.1	17.8
NE	-0.43 (-11.6)	-0.17 (-4.4)	-0.10 (-2.61)		700	18.2	39.9
E	-0.49 (-35.7)	-0.13 (-9.9)			3882	29.3	806.6
SE	-0.39 (-24.9)	-0.24 (-15.2)		-0.10 (-5.9)	3731	22.4	269.8
S	-0.36 (-25.6)	-0.31 (-21.4)	0.04 (2,6)	-0.17 (-11.7)	4437	21.7	308.8
SW	-0.23 (-17.2)	-0.16 (-12.6)		-0.27 (-18.9)	5441	16.3	264.9
W	-0.24 (-13.7)	-0.09 (-5.4)	0.11 (6.4)	-0.13 (-6.9)	3542	13.7	141.3
NW	-0.28 (-10.9)	-0.11 (-4.3)		-0.34 (-12.2)	1212	24.9	101.6
C	-0.30 (-7.4)		-0.24 (-5.9)		559	12.1	26.5

Explanations, see Tables 1 and 2.

to around 92% for W and NW winds. The highest pressures, >1007.5 hPa, were recorded for air from northerly directions: N, NE and NW, while the highest wind velocity, on average > 2 m s^{-1}, was recorded for winds from W, SW and S. Meteorological conditions prevailing for the E wind which most strongly determined the size of the concentrations of SO_2 among all wind directions (Table 4), included below-average air temp. (3.5°C) and below--average average humidity (89.1%) (Figure 10). In these conditions, the highest SO_2 level in the air, 14.3 μg m^{-3} (Figure 3), was recorded.

Winter air temperatures in the individual years of the analyzed period ranged from 11.9°C to 6.7°C, with the lowest recorded in 2006 and 2011 for NE wind (Figure 11). The warmest air from S and SW, was recorded in 2013, 2014 and 2015. No such distinct differences were found for the relative humidity of the air. The most humid air, amounting to > 90%, was recorded mainly in the years 2007-2013 for winds blowing from almost all directions. Atmospheric pressures > 1010 hPa were recorded in 2005-2008 during winds from N, NE, W and NW, while in 2011-2012 and 2015 from N, NE and E. In the winter season the weakest winds were found in 2006-2013, from N, NE, and E, and additionally in 2009 and 2012 from SE. The strongest winds

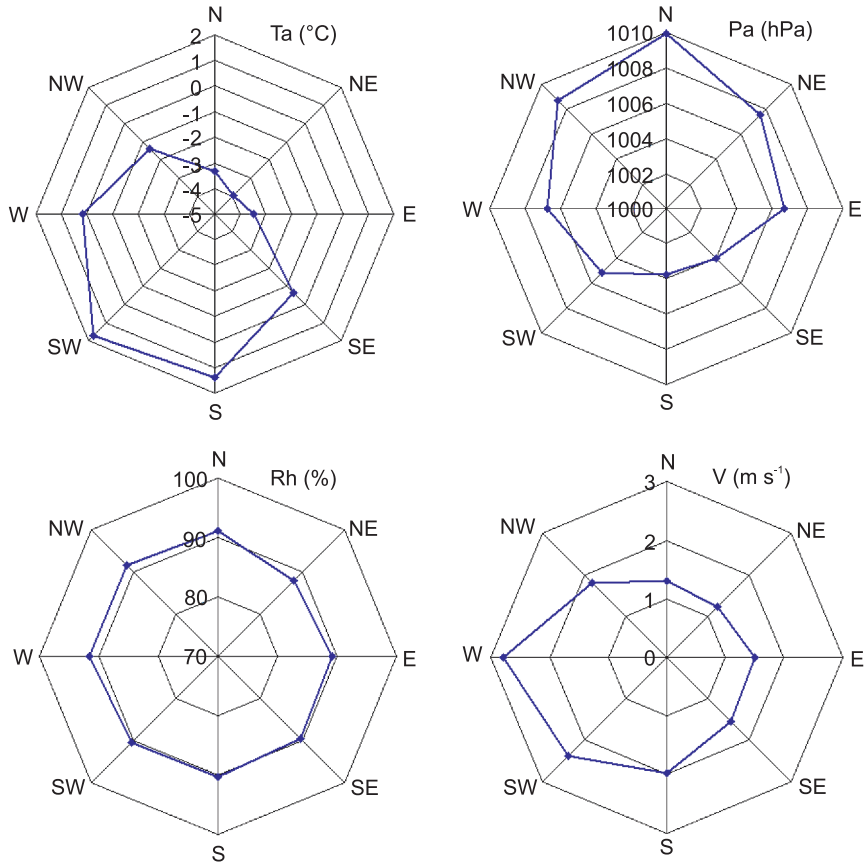

Fig. 10. Winter distribution of meteorological elements: Ta, Rh, Pa, and V, depending on the wind directions. Years 2005-2016

were from SW and W, i.e. from the directions at which the lowest concentrations of SO_2 (Figure 4) were recorded in all considered years.

DISCUSSION

Most air pollutants can be found within the Planetary Boundary Layer (PBL), the layer of the troposphere adhering directly to the Earth's surface and directly affected by the substrate (Czarnecka et al. 2016, Wang et al. 2017, Yuchechen et al. 2017). The height of the PBL can range from several hundred meters at night to several kilometers during the day, depending primarily on a geographical location as well as the season of the years or time of the day. Short-term significant and turbulent air flows play a major role in the formation of pollutants in this part of the atmosphere. Beside the

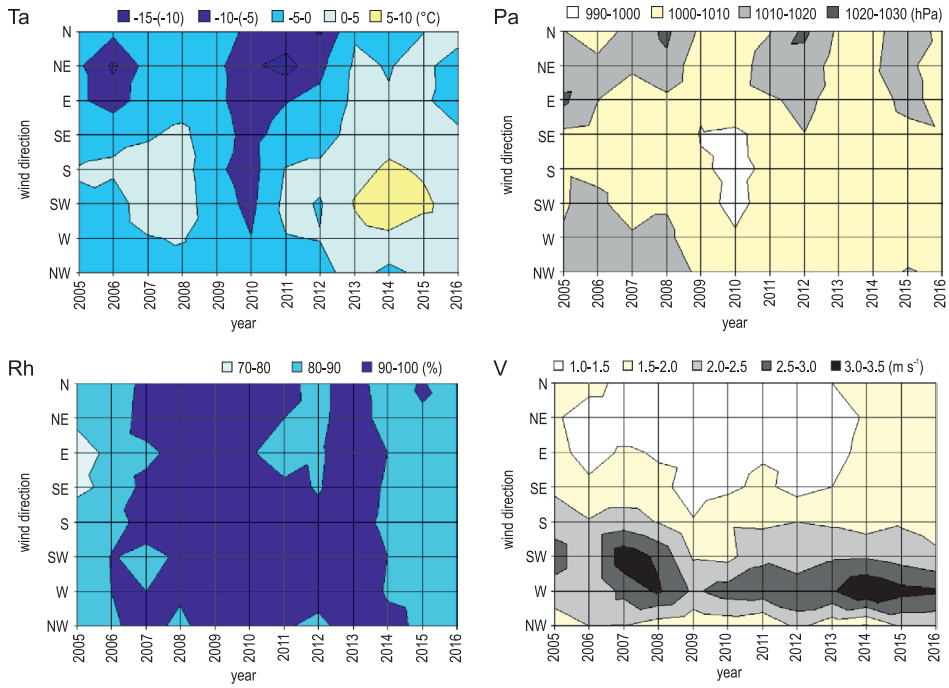

Fig. 11. Winter distribution of meteorological elements: Ta, Rh, Pa, and V, depending on the wind directions in the individual years of the analyzed period

thermal and dynamic conditions responsible for the stability of the atmosphere, a significant role in the spread of gaseous pollutants is also played by meteorological elements and wind direction (Tecer, Tagil 2013, Syafei et al. 2014, Civan et al. 2015). The weather is partly responsible for the seasonal and diurnal variability of sulfur dioxide (Miczyński et al. 1998), which has been demonstrated in this work based on measurements in the period 2005--2016. Models presenting the level of SO_2 in the atmosphere in different areas have been created by researchers such as Rúa et al. (1999), Giannitrapani et al. (2007), Juda-Rezler et al. (2011), Rivera-González et al. (2015), Dai, Zhou (2017).

Air temperature (Ta) influences SO_2 levels, and shapes the conditions of a thermal-dynamic equilibrium, so it is definitely important in the modeling of SO_2 levels in the air. The negative impact on the level of SO_2, shown between 2005 to 2016, can be explained by the increased heating demand of houses and increased energy consumption by industry, as well as a decrease of Ta itself and other weather conditions in winter (Kalbarczyk, Kalbarczyk 2008, Chattopadhyay et al. 2010, Barbulescu, Barbes 2017). A significantly higher concentration of SO_2 in the coldest months of the year was also confirmed by the research by Cichowicz et al. (2017) carried out in eastern Wielkopolska. A negative correlation between the concentration of

SO_2 and Ta (air temperature) was confirmed by the research done at various locations (Khattak et al. 2014, Syafei et al. 2014). High air pressure, especially in winter, is associated with higher pollution than low air pressure, being usually associated with higher air temperature, as evidenced by the recorded climatic conditions in Poznań. High air pressure results in the cooling of ground-level air, accompanied by reduced Ta, as well as a lack of clouds and no or weak winds (Walczewski 2000). This state of the atmosphere contributes to the formation of a stable atmospheric equilibrium, including ground-level or elevated inversions. Above-average air humidity without precipitation may promote a decrease in the concentration of SO_2, which can be likely explained by the process of elution of pollution particles at high air humidity. Differently, in the research by Cichowicz et al. (2017) the correlation between the concentration of SO_2 and relative humidity was positive. A minor effect of precipitation on the improvement of air quality at ground level, observed most frequently, is explained by the course of the processes accompanying cloud formation in the atmosphere. In turn, the negative effect of wind velocity on SO_2 levels which was recorded in all seasons in 2005-2016, can be explained by the presence of long-lasting windless weather or low wind speeds. The lack of a positive correlation between the concentration of SO_2 and wind velocity was shown by Cichowicz et al. (2017), according to whom in the summer with a lower wind velocity the concentration of SO_2 was also lower. The observed impact of easterly winds on the level of SO_2 in the air was most directly associated with the location of the coal-fired power plant in Poznań in relation to the measuring station, and also the urban structure of the city, which has a significant impact on the size of the roughness coefficient. Similar relationships in winter and summer were observed by Cichowicz et al. (2017), and in cities in northwestern Poland by Kalbarczyk, Kalbarczyk (2007).

CONCLUSIONS

In the period 2005-2016, the SO_2 concentration distribution in Poznań (mid-west Poland) was characterized by a marked seasonal and monthly variation; more than 3 times higher concentration was recorded in winter (7.8 $\mu g\ m^{-3}$) than in summer (2.5 $\mu g\ m^{-3}$). The highest average SO_2 concentration, fluctuating from 10.5 to 14.3 $\mu g\ m^{-3}$, was recorded in winter during easterly winds: E, NE and SE, which can be explained by the location of coal-fired heating and power plants relative to the air quality measurement station.

High SO_2 levels according to the WHO, above 20 $\mu g\ m^{-3}$, were most often noted in winter during E winds and in the summer for SE winds, respectively with a frequency of approx. 50% (869 recordings) and 48% (40 recordings).

Most often, from approx. 50% in winter to approx. 86% in summer, the measurements of SO_2 were below 5 μg m^{-3}; in summer twice as often at night than around noon.

The correlation coefficient determined for the weather-SO_2 relationship depended not only on the season, but also on the time of day and the wind direction. The level of SO_2 concentration significantly depended on the meteorological conditions, from approx. 9% in summer to approx. 38% in winter; negatively to air temperature, relative humidity and wind speed, and positively to atmospheric pressure in winter. The closest, R^2~29%, correlation between SO_2 and the set of meteorological elements was proven in the winter season during E winds.

In the period 2005-2016, the highest average SO_2 concentration, 14.3 μg m^{-3}, was recorded during winter and with E wind, accompanied by below-average air temperature (Ta = -3.5°C), average relative air humidity (Rh = 89.1%), average atmospheric pressure (Pa = 1006.7 hPa) and below-average wind velocity (V = 1.6 m s^{-1}).

On the basis of the research, it can be concluded that the variability in concentrations of SO_2 in Poznań is affected by the heating season and location of the city's heat and power plants.

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