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The efficiency of PM_{10} scavenging from troposphere as a function of type and duration of wet deposition

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Abstract

The article presents the results of experiments concerning tropospheric PM_{10} scavenging in wet deposition processes. Only the influence of large-scale rainfall was tested. The results presented show the effectiveness of PM_{10} scavenging under no-wind conditions. The changes in PM_{10} concentrations before, during and after the presence of rainfall were studied from 2006 to 2013. The study was conducted in an area remote from anthropogenic sources of emission. To determine the meteorological conditions, a DAVIS weather station was used. A concentration of PM_{10} was calculated with the reference gravimetric method (a PNS HVS 16 dust monitor). One hundred and nine measurement series were carried out. PM_{10} concentration was measured at 0.5 h intervals. Measured rainfall intensity ranged from 0.2 to 24 mm/h. The degree of self-purification of the atmosphere from the particulate matter was affected by the duration and intensity of the rainfall. For near-to-ground troposphere PM_{10} scavenging coefficient (Λ) does not assume different values for rainfall with the same intensity. Comparative analysis showed that the efficiency of removal of PM from the air (ΔS) was about 35% higher for heavy (>4 mm/h) than light (<0.5 mm/h) rain. The results show that the growth rate of PM_{10} concentration after rainfall episodes is twice as high in the case of light rain. The calculated scavenging coefficient Λ (which ranged from 2.47E-05 for drizzle to 2.31E-04 for heavy rain) was compared with the results obtained by a mathematical model. It was shown that the scavenging coefficient calculated on the basis of the theoretical model provided a value smaller by one order of magnitude than the coefficient determined by experimental testing. A linear relationship was found between the intensity and duration of rainfall and the value of PM_{10} concentration. Therefore, in the case of large-scale precipitation, it can be concluded that these parameters allow easy estimation of the self-purification of tropospheric air particulates.

Keywords: Background area; frontal rainfall; PM_{10}; scavenging; wet deposition

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1. Introduction

There are two main forms of particle deposition by the troposphere; dry and wet. In the case of wet deposition, “rain scavenging is generally classified as rainout - particles serving as cloud condensation nuclei or undergoing capture by cloud water and as washout - the removal of below-cloud particles by raindrops as they fall” (Chate et al., 2003). In Poland, because of the specific structure of emitted particulate matter, dry deposition has limited impact on atmospheric purification by suspended particles. On the other hand, below-cloud scavenging by rain is one of the major phenomena that control the removal of atmospheric pollutants from the air. The literature contains much information about removal mechanisms and field experiment results connected with rainfall efficiency in scavenging processes (Laakso et al., 2003; Viana et al., 2003; Kulshrestha et al., 2009; Castro et al., 2010; Connan et al., 2013). The authors tend to focus on the effectiveness of the washout of solid particles of specific size under specific rainfall types, and there is a lack of information about long-term field experiments on the effectiveness of the scavenging by large-scale precipitation of varying intensity in the absence of wind and direct insolation conditions.

In this paper, the main purpose was to estimate the scavenging efficiency of PM_{10} by large-scale precipitation under no-wind conditions in a background area. Results were obtained for long-term observations. The research hypothesis assumed that PM_{10} scavenging coefficient for rainfall with the same intensity does not have different values regardless of when the process occurs.

2. Materials and methods

Measurements were taken over eight seasons (from 2006 to 2013), which included observations of air self-purification by rain within a background area near to the village of Kotórz Mały, Poland (50^{o}43’36”N; 18^{o}0’24”E). The measurement point was situated about 520 metres from the last house in the compact settlement of the village. Only the influence of large-scale rainfall was tested. The presented results show the effectiveness of PM_{10} scavenging under no-wind and no direct insolation conditions. The changes in PM_{10} concentrations before, during and after the presence of rainfall were studied from 2006 to 2013. The study was conducted in an area remote from anthropogenic sources of emission. To determine the meteorological conditions, a DAVIS weather station was used. The concentration of PM_{10} was calculated with the reference gravimetric method (a PNS HVS 16 dust monitor). One hundred and nine measurement series were carried out. PM_{10} concentration was measured at 0.5 h intervals to minimise the influence of other factors on changes in the concentration of dust.

In the simplest approach, the assumption that the scavenging processes are the only way to remove particulates, the scavenging coefficient can be determined from measurements, knowing initial concentration c_0 at time t_0 and the concentration c_1 at time t_1 (t_1-t_0 is the time duration of the precipitation), using equation 1 (Hameed & Sperber, 1986);

$$\Lambda(d_p) = -\frac{1}{t_1 - t_0}\ln[\frac{c_1(d_p)}{c_0(d_p)}] \tag{1}$$

Of course, the scavenging coefficient depends on the aerodynamic diameter of particles (*dp*), but due to the measurement methodology the entire fraction less than 10 microns was separated. Table 1 presents the precipitation data for the eight years under study.

Table 1. Precipitation data for eight years campaign at background area.

Type of rain	**Light rain (drizzle)**	**Moderate rain**	**Heavy rain**
Rain intensity [mm/h]	0.2 - 0.5	0.5 – 4.0	4.0 – 24.0
Number of episodes	34	50	25
For cold season (Oct – Mar)	19	26	14
Form warm season (Apr – Sep)	15	24	11
Total precipitation [mm]	14.8	135.1	198.1
Percent of total 8-years [%]*	0.32	3.24	7.01

*In comparison to all types of hydrometeors falling under all weather conditions.

For convenient presentation, the effectiveness of PM_{10} removal by precipitation is also shown as a simple relationship of percentage change in the concentrations before (S_0) and after (S_t) episodes of rain [2];

$$\Delta S = \frac{S_t - S_0}{S_0} \cdot 100\% \qquad (2)$$

3. Results and discussion

As can be seen in Fig. 1, the degree of self-purification of the atmosphere by the particulate matter is mainly affected by the intensity of the rainfall. There is a great linear correlation between these two parameters (R = 0.97). To check the research hypothesis the Wilcoxon test was used. The two-tailed critical confidence level was considered and the critical p-value was 0.05.

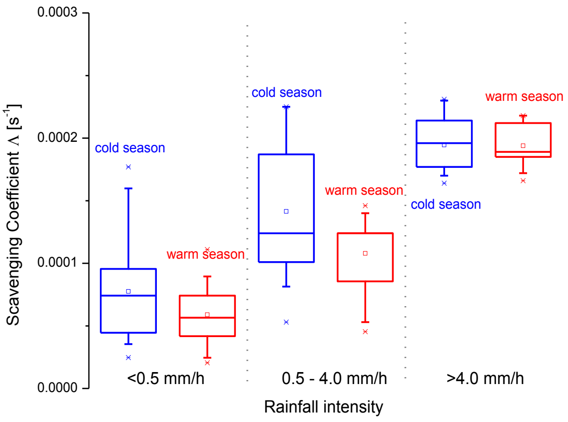

Fig. 1. Scavenging coefficient as a function of rainfall intensity (boxes show the range between the 25th and 75th percentiles. The whiskers extend from the edge of the box to the 5th and 95th percentile of the data. The horizontal line inside indicates the median value. The small square inside indicates the average value).

For light, moderate and heavy rains, there are no significant statistical differences between scavenging coefficient values. The p-values for all types of rains take the values above the significance level of the test and are respectively 0.259 for light rain, 0.056 for moderate rain and 0.648 for heavy rain. The hypothesis that the PM_{10} scavenging coefficient (Λ) for rainfall with the same intensity does not have different values regardless of when the process occurs was confirmed for all cases.

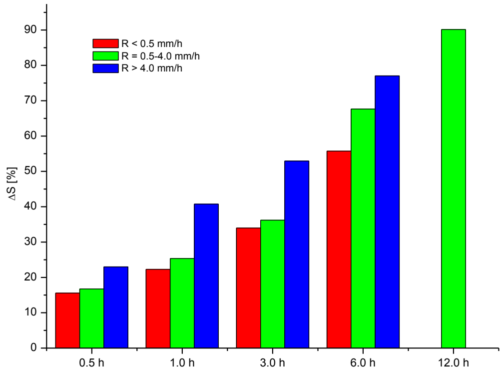

Fig. 2. Efficiency of removal PM_{10} as a function of the rainfall duration and intensity.

Fig. 2 shows the removal efficiency of PM_{10} as a function of precipitation duration. As can be seen, for all types of rainfall, there is a linear relationship between particulate removal efficiency and rainfall duration. The correlation coefficient R is 0.92, 0.94 and 0.97 for light, moderate and heavy precipitation, respectively. For example, comparing rainfall of similar intensity, we can conclude that in remote areas six hours of rainfall are about 3.5 times more effective in removing particulates than half an hour. Comparative analysis showed that the efficiency of removal of PM from the air (ΔS) was about 35% higher for heavy (>4 mm/h) than light (<0.5 mm/h) rain.

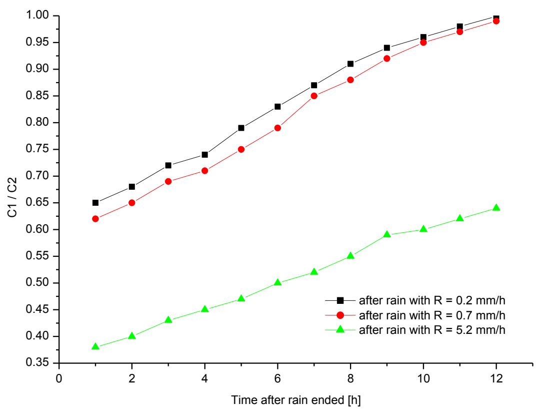

Fig. 3. The growth rate of PM_{10} concentration after rainfall episodes.

Comparison of the growth rate of PM_{10} concentration after rainfall episodes shows that for light rain it is around twice as high as for heavy (Fig. 3). In an area with limited impact of anthropogenic sources, and in the absence of horizontal movement of air, heavy rain effectively inhibits the process of re-suspension from the ground and plant surface. Of course, immediately after precipitation stops, the coefficient C1/C2 is much higher after light rain than after heavy. On the other hand, the difference between C1/C2 for light and heavy rain slowly but consistently increases with time.

Table 2. Average scavenging coefficient L for PM_{10}. Comparison for different rain intensity. Field experiment results versus numerical model data.

Rain intensity [mm/h]	**< 0.5**	**0.5 – 4.0**	**> 4.0**
Λ (experiment) cold seasons	7.24E-05	1.24E-04	1.85E-04
Λ (theoretical calculation) cold seasons			
Λ (experiment) warm seasons			
Λ (theoretical calculation) warm seasons			

In many studies, in order to assess the effectiveness of particle scavenging by rain the authors take a theoretical approach. Comparison of the results obtained from modelling and field experiments has shown significant discrepancies (Duhanyan & Roustan, 2013). In the present study, the modelling results were compared with the results of the observation field. For theoretical studies the classical approach was used. The model's parameterisation takes into account:

- raindrop size distribution (RSD), based on exponential Marshall-Palmer distribution (Marshall & Palmer, 1948),
- particle size distribution (PSD) for rural particles (Jaenicke,1993),
- terminal velocity of raindrops (Kessler, 1969),
- collision efficiency between droplets and particles (Slinn, 1983),
- scavenging coefficient for rural PSD (Andronache, 2003).

The calculated scavenging coefficient *Λ* (which ranged from 2.47E-05 for drizzle to 2.31E-04 for heavy rain) was compared with the results obtained by a mathematical model. It has been shown (Table 2) that the scavenging coefficient calculated on the basis of the theoretical model provides a value that is smaller by one order of magnitude than the coefficient determined by experimental testing. A possible explanation for these differences is presented in the articles by Goncalves et al. (2000) and Chate (2011).

4. Conclusion

In relation to the near-to-ground troposphere the PM_{10} scavenging coefficient (Λ) does not assume different values for rainfall with the same intensity. There is a significant linear relationship between the intensity and duration of rainfall and PM_{10} removal efficiency; thus, in the case of large-scale precipitation (without wind conditions), these parameters allow easy estimation of the self-purification of tropospheric air particulates.

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