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THE REMOVAL EFFICIENCY OF DUST DURING SHORT-TERM RAINS - VERIFICATION OF ADDITIONAL FACTORS

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Abstract: This paper reports the results of a comparison of the results of field study concerned with the effectiveness of PM10 scavenging by liquid precipitation in a warm and cold season of the year. The aim of this study involved: - verifying if the value of the removal coefficient (ΔC) is relative to the duration of the phenomena of wet deposition, - verification of a hypothesis that the initial value of PM concentration does not affect the value of ΔC_{PM10}. The registration of the variability of PM concentrations was undertaken over the period of seven years in the conditions of the occurrence of convective and large-scale precipitation and it was performed in a non-urbanized area. The analysis involved 344 cases of observation with the constant time interval of 0.5 h. The measurements of PM10 mass concentration was performed with the aid of a reference method accompanied by concurrent registration of the basic meteorological parameters. It was indicated that the value of the removal coefficient assumes similar values in the cold and warm season for all types of precipitation with the mean intensity of $R > 0.5$ mm h^{-1}. It was additionally noted that the effectiveness of PM10 removing by precipitation with various origin does not statistically vary according to the season. It was indicated that for precipitation with a low intensity, the values of the mass concentration of particulate matter in the ground-level zone could affect the values of the removal coefficient. It was also concluded that the diverse structure of wet deposition with a small intensity plays an important role in the process of the scavenging of solid particulate matter from close-to-ground troposphere.

Keywords*:* precipitation, PM10, scavenging process, background area

Introduction

Below-cloud scavenging plays the role of a principal process which ensures the removal of pollutant from the ground-level zone and takes on a principal role in the maintenance of high environmental qualities of the air at the expense of other components of the natural environment [1]. Therefore, it forms one of the major processes by which a balance is maintained between the inflow and outflow of aerosol particles [2]. Wet below-cloud scavenging includes all phenomena, which lead to the washing out particulate matter together with all forms of precipitation: rain, snow, fog and ice. According to [3], from the point of view of human well-being and quality of the ground-level zone, below-cloud scavenging seems to play a more important role than in-cloud scavenging. This statement is confirmed by the remark that the particulate matter which poses immediate danger to the human health is principally deposed as a result of below-cloud scavenging, while the mechanism which plays a major role in it is associated with the collision of solid particles with rain drops [4]. The process of wet aerosol washout is inherently complex as it is affected by a number of external phenomena, which include: drop size, distribution of particle sizes, chemical composition of water, rainfall intensity

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ambient temperature as well as chemical and physical properties of drops and aerosol and the area of the collision between the aerosol and rainfall drops [5].

The actual effects of the scavenging of the solid particles suspended in the atmosphere which accompanies precipitation is usually determined on the basis of the scavenging coefficient Λ [s^{-1}], and it is considered to be the most important parameter to characterize below-cloud particle washout [6]. For a particle with a given size, scavenging coefficient is the function of the boundary velocity of the droplet and effectiveness of the collisions between rainfall droplets and the particles in the atmospheric aerosol [7]. However, as it was noted, due to the great number of the factors which play a role in the processes occurring below-cloud, the values of scavenging coefficient are characterized by a considerable variability [8].

The aerosol scavenging coefficient can be defined in terms of the bulk particle number, bulk particle mass, or size-resolved particle number and mass concentration. The bulk approach directly measures or models the average precipitation rate and the variation of aerosol mass. Results from a bulk approach can be substantially different from a more detailed one with size spectra included [9, 10]. A size resolved particle and droplet experimental approach requires measurements during the considered events of the size distribution of the aerosol and of the droplets. The adopted methodology of observation (in current article) does not allow to meet the criteria presented above. In the other hand, the effectiveness of PM10 removal by precipitation can also be shown as a simple relationship of percentage change (ΔC) in the concentrations before (C_0) and after (C_t) episodes of rain (to distinguish, the ΔC will be called the removal coefficient instead of the scavenging coefficient).

Experimental studies into below-cloud purification performed in actual conditions focus on various aspects of this process. The processes are researched both on a complex scale, i.e. with details of the effectiveness of solid particle removing by the particular types of precipitation, as well as on a specific scale, when a study can involve the effectiveness of scavenging of particular particle types by the specific types of precipitation. Experimental studies often occur through measurements in the direct vicinity of anthropogenic sources of emissions, both in urban and rural areas [8, 11]. It is reasonable to remark at this point that a vast proportion of the studies was conducted on a local scale, while on the other hand, local emission of pollutants and the structure of rain clouds has a considerable effect on the characteristics of wet deposition [1]. Besides, the variations in the concentration of aerosols in the troposphere after incidences of precipitation can occur in the adjacent as well as remote areas [7].

The variation in the concentration of aerosols in two successive time intervals in the actual conditions is relative to a number of phenomena, such as turbulence in the boundary layer, chemical processes in the liquid phase as well as potential emission and transport of pollutants from the more remote areas [12]. One could risk putting a question at this point: does the lack of a uniform value of the removal coefficient result from the sole effect of the above mentioned parameters? Could it be that the variability in the value of ΔC is due to other, more ordinary reasons?

The studies into the effectiveness of removing coarse particles in the processes of wet deposition have a primarily theoretical inclination (that is they involve numerical studies), in which weather conditions specific for a particular area and the season are not considered.

An insight into the existing literature also yields that the effect of the concentration of aerosols in the air directly before the incidence of a rainfall has not been sufficiently recognized and researched as a factor which affects the value of percentage change in the concentrations before and after episodes of rain. Besides PM10 is still one of the most important air quality indexes. Hence, a decision was made to compare the effectiveness of removing PM10 by the liquid precipitation in the cold and warm season of the year. In addition, an attempt was made to estimate the effect of the initial concentration of PM10 on the value of ΔC.

The principal objective of the research involved verification of hypotheses regarding the following:

- for specific intensity ranges and types of liquid precipitation, the value of removal coefficient ΔC_{PM10} is the same in the cold and warm season (I),
- for specific ranges of precipitation intensity with various origin, the effectiveness of particles removing is the same in the cold and warm season (II),
- for specific ranges of precipitation intensity, the initial value of the concentration does not affect the value of ΔC_{PM10} (III).

Materials and methods

The testing was performed over a period of 7 successive years (2007-2013). In order to minimize the effect of anthropogenic sources, the concentration of PM10 was measured in an undeveloped area, i.e. in the vicinity of a village (Kotorz Maly, Poland, 50°43’37”N; 18°03’22”E, 1,025 inhabitants). The measurement point was located in an open, yet shielded meadow area protected by the surrounding wood - 11 km from the border of a provincial town (Opole, 122,000 inhabitants) and 2 km from the nearest compact rural building development. The measurement campaign involved the observation of the PM10 concentration resulting from the occurrence of two types of precipitation (frontal and convective ones) with different intensity R.

The procedure by which the measurement of the concentration of PM10 was performed was in conformity with the European standard [13]. The aspiration of the PM10 in the air was carried out by a MicroPNS HVS16 (UMWELTTECHNIK MCZ GmbH®) sequential dust sampler. The aspiration headers were installed 2 m above ground level. The flow rate was 68 $m^3 h^{-1}$. The PM separators applied Whatman GF/A fibreglass air filters with a diameter of 150 mm. The aspiration at a constant time interval of 0.5 h was conducted directly before and during the occurrence of precipitation. The expanded mass concentration measurement uncertainty (U) did not exceed 3.2%. The time interval guaranteed the PM collection to a degree that was sufficient to determine the mass of the captured particulate matter, even in conditions when its concentration in the air was low. The initial testing (n = 25, time interval of registration - 10 seconds, time of a single registration - 1800 seconds) using a DustTrak 8520 Aerosol Monitor - TSI®, was conducted in variable weather conditions; however, with the exception of rain, it did not yield considerable differences in the results of PM10 concentration over 10 and 1800 seconds in the investigated area.

To determine the meteorological conditions, a portable weather station (DAVIS®) was used, which is widely used for registration of weather conditions in field measurements

[14]. This weather station was installed 12 m from the PM sampler. The sensors, which determined relative humidity (*RH*), temperature (*T*), atmospheric pressure (*P*), wind speed (*Ws*), wind direction (*Wd*) and rainfall (*R*), similarly to the case of the dust sampler aspiration header, were installed at a height of 2 m above the ground.

The removal coefficient of the particulate matter was determined with the relation (1):

$$\Delta C = \frac{C_t - C_0}{C_0} \cdot 100\% \tag{1}$$

The proposed solution has a primarily practical character and constitutes an attempt to offer a way of approaching the effect of scavenging of particulate matter suspended in the ground-level zone.

As the scavenging coefficient Λ, the removal coefficient ΔC is relative to the aerodynamic diameter of the PM; however, due to the applied measurement methodology, the entire fraction of PM with the diameter below 10 μm was identified. The values of the removal coefficient were derived on the basis of 30-minute mean mass concentrations of PM10.

All statistical operations were undertaken by means of the STATISTICA 13.1® program.

Results and discussion

Meteorological parameters

The measurement campaign conducted over 7 years yielded the results of 344 cases of a potential change in the mass concentration of PM10 accompanying the occurrence of liquid precipitation. A descriptive characteristic of meteorological parameters which characterize the conditions of the observations is found in Table 1. In total, around 46% of observations involved convective precipitation (including 25 cases of observations of variations in PM10 mass concentrations accompanying storms). During the cold season (November to April), the analysis involved the observations regarding 20 instances of convective precipitation and 98 large-scale ones. The majority of observations was taken during the warm season (May to October), i.e. 140 for occurrences of convective precipitation and 86 for large-scale ones. The highest number of cases (around 48%) corresponded to light precipitation types with the intensity $R \leq 0.5$ mm h^{-1}. However, light precipitation was not observed for instances of storms. Around 70% cases of the occurrence do light precipitation were registered during the warm season. The mean precipitation, in the range from 0.6 to 2 mm h^{-1} (with a total number of 108), was registered 47 times during the cool season (including 13 instances of convective precipitation). In addition, 42 cases (including 26 in the cold season) involved rainfall intensity in the range from 2.1 to 5 mm h^{-1}, where the proportion of large-scale rainfall amounted to 22%. Over 93% cases of heavy precipitation (> 5 mm h^{-1}) occurred in the form of convective precipitation in the warm season. This type of precipitation was most common during storms (i.e. in 16 out of 29 instances) and incidentally during large-scale precipitation - in around 7% of cases.

During the duration of the observations, the relative humidity was characterized with small variability and its value was comparable during all instances of precipitation. In regard to the observed convective precipitation, small variability in the ambient air temperature was additionally observed. The greatest variability in terms of this parameter was noted for large-scale precipitation and could be mainly associated with cold fronts. Beside the intensity of hydrometeors, high variability was noted for the velocity of horizontal air masses. Nevertheless, during the measurement campaign, 21% of instances of precipitation were not accompanied by wind. The horizontal movement of air masses were registered in the north (47%) and south direction (31%), i.e. from the areas with high quality of the environment and low air pollution [15]. Only in 13% of cases (i.e. with wind in the west and north-west), the incoming air masses originated from areas with high anthropogenic pollutions levels i.e. from the area of Opole city with severe PM10 pollution as well as from the surrounding areas of rural development.

Table 1

Meteorological parameters characterizing the conditions during the observations

Type of precipitation period	**Descriptive statistics**	T **[°C]**	RH **[%]**	R **[mm h^{-1}]**	Ws **[km s^{-1}]**	**PM10** C_0 **[µg m^{-3}]**
Convective Cold season	avg	14.1	0.85	1.1	3.2	18.9
	med	13.6	0.89	0.9	1.9	19.0
	SD	3.7	0.09	0.93	3.13	10.7
	min	8.5	0.66	0.2	0.2	5.10
	max	18.4	0.94	4.5	11.7	42.0
Convective Warm season	avg	17.7	0.79	3.0	3.5	18.6
	med	15.3	0.81	1.3	2.7	19.0
	SD	4.41	0.12	4.75	3.32	8.01
	min	12.8	0.69	0.2	0	3.40
	max	28.4	0.95	37.0	16.8	48.0
Frontal (large scale) Cold season	avg	7.6	0.83	0.6	4.1	20.9
	med	7.7	0.86	0.4	2.2	21.0
	SD	3.4	0.10	1.27	4.93	7.79
	min	0.0	0.73	0.2	0	3.00
	max	14.7	0.99	13.0	24.0	63.0
Frontal (large scale) Warm season	avg	13.5	0.85	0.9	4.2	19.0
	med	13.3	0.88	0.5	2.5	18.0
	SD	3.74	0.09	0.83	5.87	8.56
	min	6.1	0.69	0.2	0	4.90
	max	27.2	0.94	5.1	27.3	59.0

Removal coefficient in cold and warm season

An initial analysis with the application of the Kolmogorov-Smirnov test indicates that the registered values of the specific meteorological parameters and the calculated values of the removal coefficient (ΔC) are not characterized with normal distribution. Consequently, all statistical analyses which were used to verify the initial hypotheses had to apply non-parametrical tests.

The analysis of all collected results, not accounting for the identified types of liquid precipitation and times of its occurrence confirms the general approach that the removal coefficient is considerably correlated with intensity of precipitation. On the basis of the Guilford scale [16], one can note that the results of the observations indicate a considerable degree of correlation between ΔC and R (Spearman correlation coefficient $rho = -0.85$). The value keeps its relevance level at $p\text{-}value < 0.01$. The calculated determination coefficient makes it possible to risk a statement that the rainfall intensity is responsible for explaining around 73% of the variability in the value of Δ*C*. The results of the variability in PM10 mass concentration and calculations indicate that within the range of the precipitation *R*: 0.2-37.0 mm h^{-1}, the value of Δ*C* is found in the range from 0.00 to –93.0% with a median equal to –12.0% for R_{MED} = 0.6 mm h^{-1}. Absence of positive values of Δ*C* means, that after short-term rainfall episodes no increase in PM10 mass concentration has been observed.

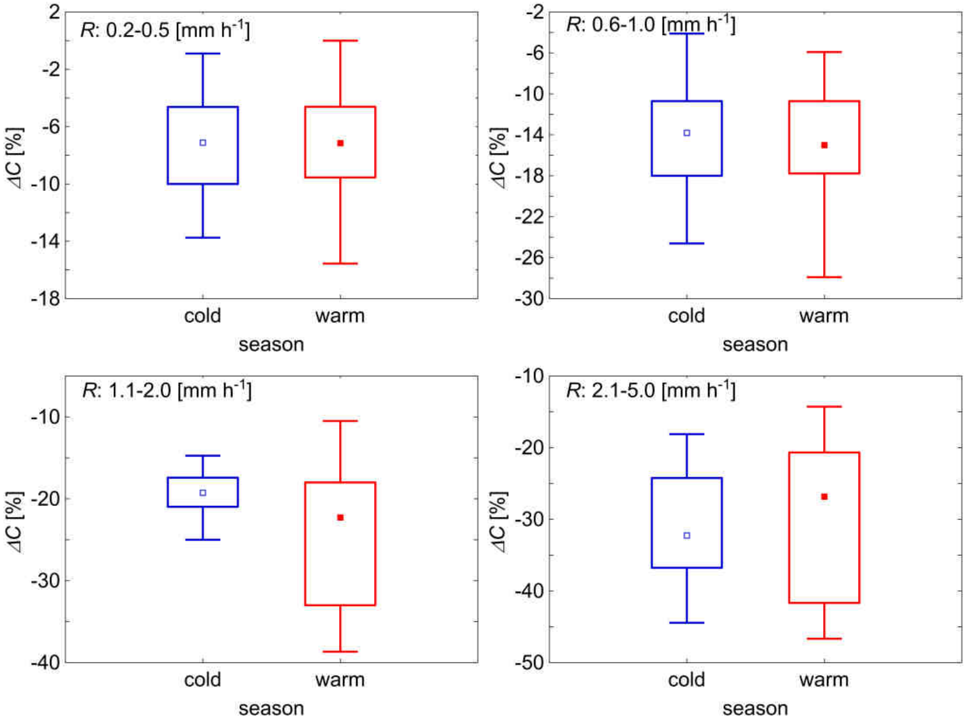

Fig. 1. Removal coefficients determined in cold and warm season as a function of rainfall intensity

Figure 1 contains box charts which illustrate the variability of the value of Δ*C* in the function of four adopted ranges of rainfall intensity for the investigated observation periods. Graphical interpretation seems to confirm the earlier statement regarding the principal reason which affects the intensity of wet deposition is associated with the effectiveness of scavenging. At the same time, it is noticeable that for the particular ranges of *R*, the variability in Δ*C* is slightly higher for the warm season. Such a condition could be attributed to the instability of quantitative parameter associated with particulate matter emission from the local natural sources occurring in the investigated area, whose activity is predominant in the warm season. The results of statistical analysis summarized in Table 2 with the use of non-parametric Mann-Whitney test indicate statistically relevant differences between the effectiveness of scavenging in the cold and warm season; however, they are only noted for precipitation with the lowest intensity. At the same time, *p-value* is affected by the results gained for $R = 0.2$ and $0.4\ \text{mm h}^{-1}$, for which, under the adopted relevance level α, the value of the test probability was lower than 0.01. One can also note that the results of the removal coefficient were slightly lower during the cold season. Apparently, this fact could also be attributed to the local atmospheric dispersion and limited transport of particles from the areas with higher pollution due to occurrence of precipitation. Consequently, this affects the level of PM10 concentration during the occurrence of the phenomenon of wet deposition. The high values of the test probability gained for the rainfall intensities of 0.6-1.0, 1.1-2.0 and 2.1-5.0 mm h^{-1} indicate that the value of median ΔC could be noted for the particular seasons. The results of statistical analysis presented in the last two columns of Table 2 contains a summary of adopted ranges of precipitation with the same origin (i.e. convective and large-scale types) and indicates very similar results, which could suggest that the type of precipitation does not affect the value of ΔC for the same intensity of wet deposition. However, it is worth noting at this point that the differences in the value of removal coefficient between the examined seasons occur solely for the case of precipitation with the smallest registered intensity. It seems that this result is affected by the structure of the wet deposition, which for the case of large-scale precipitation usually takes the form of very densely packed raindrops with a small size. Such a form of precipitation is likely to wash out pollutions from the troposphere with considerable effectiveness and this process is rather effective regardless of its duration. For the case of convective rainfall with a low intensity, the difference in the effectiveness of scavenging is more discernible. This state could also be attributed to the structure of precipitation (drops with a high speed and small drop density and lower effectiveness of collisions with solid particles) as well as to the conditions of the convective and transport of pollution mass due to advection (lower values of ΔC in the warm season, i.e. during the period with the more intense dissipation of solid particles due to bottom-up currents). The results indicate that the test hypothesis is true for all types of liquid precipitation with intermediate intensity, i.e. for $R > 0.5\ \text{mm h}^{-1}$.

Table 2

The results of Mann-Whitney test. *p-value* for two different seasons (cold and warm). Critical *p-value*: 0.05

Precipitation intensity *R* [mm h^{-1}]	**Mixed convective and frontal rainfall**	**Convective rainfall**	**Frontal rainfall**
0.2	0.006	0.004	0.024
0.4	< 0.001	< 0.001	**0.183**
0.5	**0.349**	**0.381**	**0.293**
0.2-0.5	0.039	**0.158**	**0.051**
0.6-1.0	**0.426**	**0.674**	**0.797**
1.1-2.0	**0.074**	**0.525**	**0.124**
2.1-5.0	**0.687**	to less data to compare	**0.967**

Bold values showed realization of condition of Mann-Whitney test

Figure 2 presents the ranges of the removal coefficient derived for the cold and warm season with its classification according to the distinction between convective and large-scale precipitation types. The value of removal coefficient is likely to decrease along with the increase of the intensity of both convective and frontal rains. The graphical illustration suggests differences in the values of the removal coefficient obtained for particular precipitation types. However, the analysis performed with the aid of the Kruskal-Wallis (ANOVA) test rejects this statement completely. For the case of light rainfall (for n = 177), the value of the Kruskal-Wallis test - H was equal to 6.279, and the relevance level *p-value* was equal to 0.098. For rainfall intensity in the range R = 0.6-1.0 mm h^{-1}, for the total number of observations n = 64 and R = 1.1-2.0 mm h^{-1} for n = 40, the value of H was gained at the level of 1.736 and 3.136 with the corresponding *p-values* of 0.629 and 0.371, respectively. The low values gained in the test accompanied by high relevance levels make viable the hypothesis that for the identified ranges of rainfall intensity with various origin, the effectiveness of PM10 removing from the boundary layer does not vary statistically for the warm and cold season.

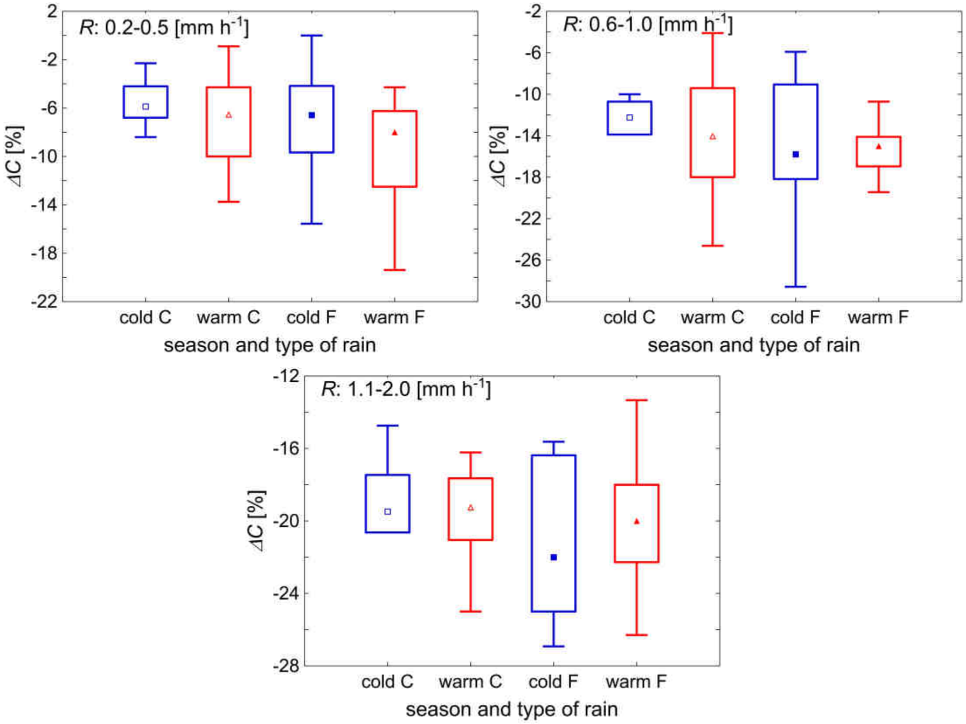

Fig. 2. Removal coefficients determined in cold and warm season as a function of rainfall intensity of two different types of precipitation (C - convective, F - frontal)

Effect of the initial concentration C_0 on the value of removal coefficient ΔC

Figure 3 illustrates the scatter of the calculated values of removal coefficient depending on the initial concentration obtained directly before the episodes of rainfall. Table 3 presents the results of the Spearman correlation between initial concentration and ΔC undertaken separately for mixed convective and large-scale precipitation types. On the basis of data in Figure 3 one can see that for mixed convective and frontal rains, along with the increase in their intensity, the correlation (ΔC – C_0) tends to disappear. Nevertheless, the results confirmed by statistical analysis indicate that for rainfall with a low intensity, the relation tends to be moderate and the value of the correlation coefficient is significant.

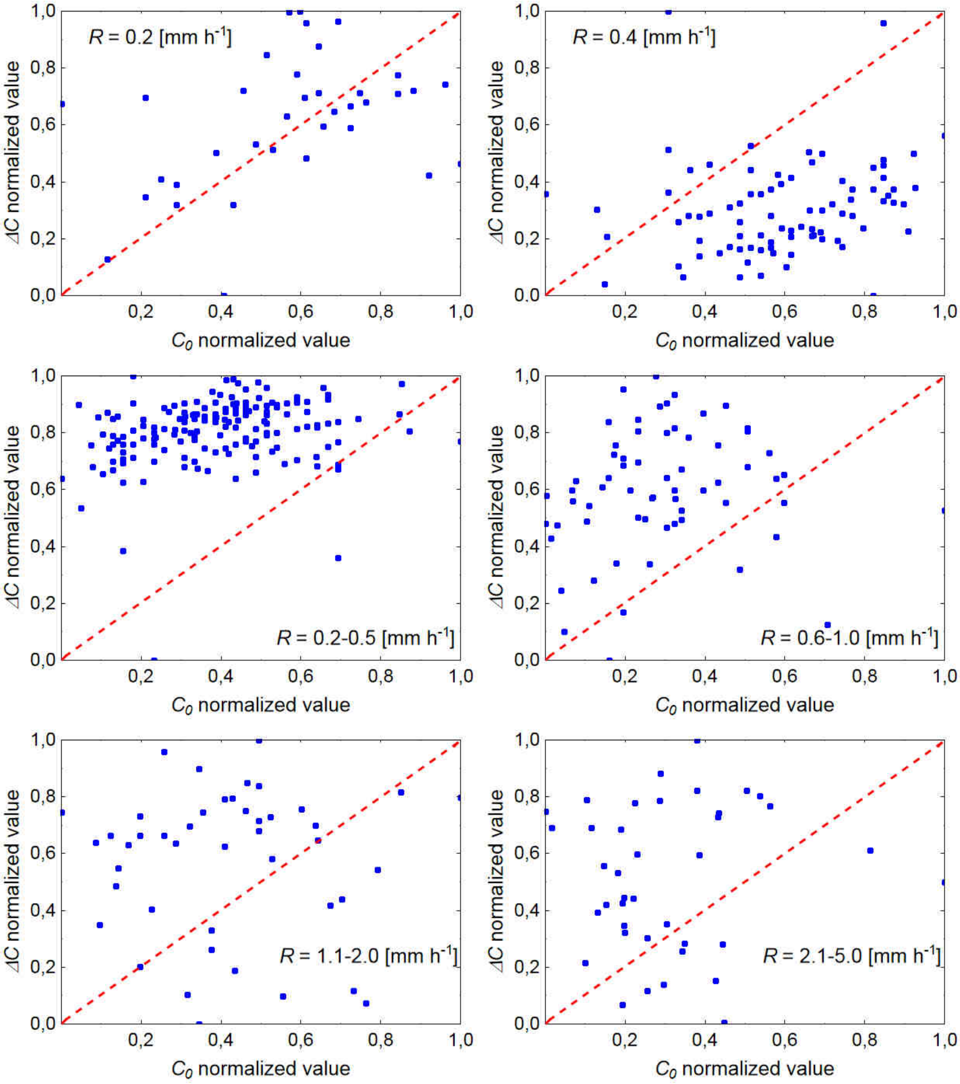

Fig. 3. Removal coefficient as a function of the initial mass concentration of PM10 for different ranges of precipitation intensity

In addition, one can note that convective rainfalls indicate a higher positive correlation ($\Delta C - C_0$) and this relation, although not always considerable, tends to keep its relevance for all investigated rainfall intensity ranges. For the case of convective rainfall with the low intensity, rain does not usually take the form of a standard drizzle, but the drops which are elongated and, thus, their ability to wash out pollutants is limited. Hence, the correlation between ΔC and C_0 is in this case very clear. For the case of large-scale rainfall, which is characterized with the smaller intensity of dynamic changes in time, the value of the initial concentration does not affect the effectiveness of scavenging during the liquid deposition with the intensity $R > 0.5$ mm h^{-1}.

Table 3

Spearman correlation ΔC - C_0 results

Precipitation intensity R [mm h^{-1}]	**Mixed convective and frontal rainfall**	**Convective rainfall**	**Frontal rainfall**
0.2	-0.659^{*}	-0.618^{*}	-0.539^{*}
0.4	-0.568^{*}	-0.338^{**}	-0.474^{*}
0.5	-0.394^{*}	-0.339^{**}	–0.325
0.2-0.5	-0.518^{*}	-0.604^{*}	-0.324^{*}
0.6-1.0	–0.228	-0.391^{**}	–0.105
1.1-2.0	–0.040	-0.348^{**}	–0.023
2.1-5.0	0.121	to less data to compare	0.098

* - significant at $p < 0.01$, ** - significant at $p < 0.05$

As reported in the studies by Aikawa and Hiraki [17] conducted for a constant rainfall intensity, the value of the scavenging coefficient assumes highest values during the initial phase of the wet deposition process. The results gained in this study do not seem to confirm this statement, as they are limited to only the first 30 minutes of the duration of precipitation, and therefore, extensive comparison is not possible on its basis (also due to different base for coefficient calculations). On the other hand, the results gained in the study indicate, that for the rainfall with a constant and low intensity, higher levels of initial mass concentration of PM10 could lead to the reduction in the value of ΔC (to better scavenging). This conclusion could to a certain degree explain the lack of conformity of the results gained by various researchers for precipitation with the same characteristics and duration of rainfall, which however, vary in terms of location and level of the immission of particulate matter suspended in the lower layers of the troposphere.

Finally, it is possible to remark that the initial hypothesis stating that for the particular ranges of rainfall intensity, the initial value of the mass concentration does not affect the value of ΔC_{PM10} could be considered to be true for large-scale precipitation with intermediate intensity. At the same time, it would be false to think that the same statement is also relevant for all registered precipitation types, without their distinction according to an origin as the results are considerably affected by the results for frontal precipitation.

Conclusions

The conducted field studies indicate that for the examined intensity range of large-scale (frontal) and convective rains, the medians of PM10 removal coefficient do not assume values which are statistically different depending on the thermal conditions which define the warm and cold season during the occurrence of wet deposition with intermediate intensity. The effectiveness of PM10 removing by precipitation with various origin (convective vs. frontal rains) does not differ statistically for the warm and cold seasons.

Nevertheless, the results could indicate that the distinct structure of the analysed forms of wet deposition, in particular for the case of their low intensity plays a major role in the process of scavenging particulate matter and could justify the evident variability in the value of ΔC. The results of field studies indicate that the initial value of dust mass concentration in the air could affect the value of ΔC_{PM10} to a limited degree during the phenomenon of wet deposition, while slightly reducing the effectiveness of removing particulate matter by light rains.

The scope of the realized research was local, nevertheless, the results could be considered to be representative for areas located remote from direct sources of enriching atmosphere with pollutant of anthropogenic origin. Generally, these results could be deemed as representative for the moderate climate. In addition, the considerable volume of observations undertaken in the conditions of the occurrence of wet deposition could contribute as complementary to the existing state of knowledge regarding effectiveness of PM10 scavenging.

The results and analysis of the conducted experiments could prove to be useful for clarifying and enabling better understanding of existing discrepancies regarding the value of scavenging particulate matter reported in the research which deals with this subject matter.

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SKUTECZNOŚĆ USUWANIA PYŁU PODCZAS OPADÓW KRÓTKOTRWAŁYCH - WERYFIKACJA DODATKOWYCH CZYNNIKÓW

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Abstrakt: Artykuł prezentuje porównanie rezultatów badań polowych nad efektywnością wymywania PM10 przez opady ciekłe występujące w chłodnym i ciepłym okresie roku. Celami artykułu było: - sprawdzenie, czy wartość współczynnika usuwania (ΔC) zależy od okresu występowania zjawiska mokrej depozycji, - weryfikacja hipotezy, iż początkowa wartość koncentracji nie wpływa na wartość ΔC_{PM10}. Siedmioletnie rejestracje zmian stężenia pyłu w warunkach występowania opadów konwekcyjnych i wielkoskalowych przeprowadzono na obszarze niezurbanizowanym. Analizie poddano 344 przypadki obserwacji o stałej rozdzielczości czasowej 0,5 h. Pomiary stężenia PM_{10} prowadzono z użyciem metody referencyjnej przy jednoczesnej rejestracji podstawowych parametrów meteorologicznych. Wykazano, że współczynnik usuwania ΔC_{PM10} przyjmuje podobne wartości w sezonie chłodnym i ciepłym dla wszystkich form opadów ciekłych o średnim natężeniu $R > 0{,}5$ mm h^{-1}. Stwierdzono, że efektywność wymywania PM10 przez opady o różnej genezie nie różni się statystycznie dla sezonu chłodnego i ciepłego. Pokazano, że dla opadów o niskiej intensywności wartość koncentracji pyłu w troposferze przyziemnej przed opadem może wpływać na wartość współczynnika usuwania. Wykazano, że odmienna struktura form mokrej depozycji o niskiej intensywności odgrywa istotną rolę w procesie wymywania cząstek stałych z atmosfery przyziemnej.

Słowa kluczowe*:* opad atmosferyczny, PM10, proces wymywania, obszar niezurbanizowany