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The impact of rainfall on the diurnal patterns of atmospheric pollen concentrations

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ABSTRACT

Atmospheric precipitation removes the majority of biological and chemical pollutants from the lower parts of the troposphere. However, some studies infer increasing atmospheric pollen concentrations during precipitation events and/or thunderstorms, which are known to trigger allergic reactions (referred to as thunderstorm-triggered asthma). The aim of this study was to determine the impacts of precipitation on the diurnal variability of airborne pollen concentrations, with particular focus on the timing and intensity of precipitation events. We also considered the impacts of other meteorological elements on atmospheric pollen concentrations. The research was conducted in Rzeszów (SE Poland) from 2016 to 2018. We used two aerobiological and two meteorological stations in this study to determine potential spatial variability in the pollen response to rainfall, the diurnal precipitation changes, and the precipitation intensity in the city area. We determined the pollen response of four pollen types: *Betula, Pinus*, Poaceae, and *Urtica*, and we only included data from days that fulfilled restrictive criteria throughout all pollen seasons. We analysed a total of 81 days, which were divided into five groups according to precipitation intensity, the time of day of a precipitation event, and the type of pollen response to precipitation. Our results suggest that precipitation intensity was the dominant control on pollen concentrations; concentrations only decreased clearly under rainfall intensities of at least 5 mm•h^{-1} and this value we recommended as threshold value for long lasting decrease of pollen concentrations in our region. Lower intensity rainfall events resulted in no change in atmospheric pollen concentrations throughout the day. We noted the occurrence of increased pollen concentration immediately before and during rainfall events. Further, other parameters were also found to influence pollen concentrations in the atmosphere, including relative humidity, the time of day, and biological factors such as the plant phenophase or the phase of a pollen season.

1. Introduction

Atmospheric precipitation improves air quality by removing the majority of biological and chemical pollutants from the lower troposphere (Gatz and Dingle,1971; Wang et al., 2012; Rathnayake et al., 2017). However, the efficiency of pollutant washout depends on the precipitation type (i.e.: rainfall, snowfall), intensity, course (i.e., intermittent or continuous) (Olszowski, 2016), and the size of rainfall drops (Gatz and Dingle,1971). Most studies on pollutant washout have focused on rainfall, and it is widely agreed that rainfall reduces the concentrations of harmful atmospheric particulate matter (PM) of the < 2.5 µm and to some extent the < 10 µm fraction (Olszowski, 2016; Rathnayake et al., 2017). The rainfall removal of airborne particles larger than 3 µm is less effective because of their tendency to collide with falling raindrops. Precipitation has been found to reduce the concentration of biological airborne particles, such as pollen grains (Ribeiro et al., 2003; Rathnayake et al., 2017). In contrast, other studies have found allergenic pollen grains and fungal spores to threaten allergy sufferers even during high rain and snowfall events (Norris-Hill and Emberlin, 1993; Venables et al., 1997; Pulimood et al., 2007; Borycka and Kasprzyk, 2018; Kasprzyk and Borycka, 2019). Allergy sufferers are therefore not always safe during precipitation periods, despite this recommendation given to patients. Moreover, symptoms are often triggered shortly before and sometimes following a thunderstorm (with or without rainfall) due to increases in air humidity (Venables et al., 1997; Thien et al., 2018), which facilitates the rupturing of pollen grains and the release of allergen-bearing respirable particles that can penetrate the lower airway (Taylor et al., 2004; Wang et al., 2012). Similar atmospheric mechanisms have also been observed for fungal spores (Pulimood et al., 2007). Allergenic particles of respirable size fractions (< 10 µm) are found to peak in concentration approximately an hour prior

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to and during rainfall events (Venables et al., 1997; Rathnayake et al., 2017). These particles are particularly hazardous during sunny days following heavy rainfall (Wang et al., 2012) under high atmospheric concentrations of pollen grains or fungal spores (Harun et al., 2019). High wind velocity before and during thunderstorms also contribute to higher atmospheric pollen concentrations (Venables et al., 1997; Thien et al., 2018). This combination of meteorological parameters can lead to serious health problems, including epidemic asthma (Thien et al., 2018). Thunderstorm-triggered asthma is a global health problem, which has led to a number of deaths worldwide (Pulimood et al., 2007; Thien et al., 2018; Harun et al., 2019). Moreover, rainy days during pollination period can contribute to less effective pollination and fertilization and in consequence to less fructification and less crops. However, this relationship is not so clear and according to many authors it is temperature that seem to be a key factor of harvest size (Minero et al., 1998; Kasprzyk et al., 2014; Bogdziewicz et al., 2017). Therefore the importance of role of precipitation in pollination and fertilization might be linked with different character of precipitation- especially its intensity. This fact is crucial in agriculture, horticulture and forestry and should be better understood.

The response of pollen concentrations to precipitation events may predominantly depend on rainfall intensity. Precipitation intensity is classified as an amount of rainfall per unit time, and the classification threshold values vary between countries (Llsat, 2001; Monjo, 2016; Glossary of Meteorology, 2018). In the warm seasons of temperate climate zones (overlapping with the main pollen seasons of mostanemophilous species), atmospheric precipitation typically manifests as showers of high or moderate intensity (Bielec-Bakowska and Lupikasza, 2009). Generally, high rainfall intensity is related to *Cumulus* (Cu) and *Cumulonimbus* (Cb) clouds, which form via convection or on the boundary of atmospheric fronts (most often cold fronts). Thunderstorms often accompany Cb clouds, which results in a number of phenomena, including 1) rainfall, which is often heavy (though thunderstorms without rainfall also occur); 2) electrical discharges; 3) turbulence: chaotic, vertical, or horizontal air movement with changeable direction and velocity; 4) wind gusts: rapid increases in the average wind velocity of 5 m•s^{-1}; 5) squall: a rapid and short-lived increase of wind velocity by a minimum of 8 m•s^{-1} when the prior average was at least 10 m•s^{-1}; 6) wind shear: rapid shifts in wind direction and/or wind velocity linked to the subsidence of air masses in the lower troposphere; and 7) downbursts: a strong current of cold air towards the ground from below the thunderstorm cloud (Doswell, 2001; Wickson, 2015; Glossary of Meteorology, 2018).

Wind characteristics strongly influence airborne pollen concentrations (Alan et al., 2018). Therefore, the abovementioned thunderstorm phenomena (mainly points 4–7) should be considered together with precipitation intensity. Downbursts occurring below Cb clouds can interfere with up-flowing air to heights of 500–1500 m. Descending cold air currents reach 80–140 km•h^{-1}, and air turbulence occurs 7–10 km and sometimes 15–30 km from the cloud centre (Doswell 2001). The hit of the wind is strongest below the front of the thunderstorm cloud; this is referred to as a microdownburst and is linked with wind shear. The currents are strongest in locations of heaviest rainfall (Wickson, 2015). Strong turbulence is linked with both Cb and Cu clouds, and the area of turbulence is usually two to three times larger than the cloud surface. Long-lasting precipitation events also occur in warmer seasons and are predominantly linked to layered clouds.

The research concerning the impact of precipitation on aerobiological phenomena are widely discussed (Norris-Hill and Emberlin, 1993; Minero et al., 1998; Ribeiro et al., 2003; Kasprzyk et al., 2014; Alan et al., 2018; Bruffaerts et al., 2018; Borycka and Kasprzyk, 2018). However, the majority of analyses do not consider the time of day of precipitation events, the precipitation intensity, and/or the diurnal variability of airborne pollen concentrations (i.e., before, during, and after the precipitation event). The authors who compiled crop forecasting models also are focused rather on precipitation sum (daily or monthly) before and after flowering period than on hourly variability in the course of precipitation (Minero et al., 1998; Kasprzyk et al., 2014). The aim of this study was therefore to determine the impact of these precipitation features on the diurnal variability of airborne pollen concentrations of four selected taxa which high amount of pollen occurred from Aprill until the beginning of September. In this analysis, we considered both the total precipitation and precipitation intensity (mm per the time unit), as well as a number of additional meteorological elements. We focused on days of high average daily pollen concentrations that were registered together with the occurrence of precipitation. We hypothesise that atmospheric pollen concentrations primarily depends on rainfall intensity. We also supposed that the time of day of precipitation events, the pollen grain type and *in situ* meteorological conditionswill exert minor influences on atmospheric pollen concentrations.

2. Material and methods

2.1. Study area

This research was conducted in Rzeszów (a middle-sized city in SE Poland; 50º02’28”N, 21º59’56”E; Fig. 1B) from 2016 to 2018. The altitude of Rzeszów oscillates between 210 m and 215 m a.s.l. The city has a dense built-up area with some green enclaves in the downtown region and more green spaces interweaved within the urban fabric of the city suburbs (Borycka and Kasprzyk, 2018). Poland is located in a warm temperate climate zone and its climate is predominantly influenced by polar-maritime transformed air masses, that are transformed during movement from the source region (north part of the Atlantic Ocean) over Europe and they partly lose their maritime features. However, the area is characterised by a high degree of continentalism, with average spring and fall temperatures of 8–9 °C, summer temperatures of 17–18 °C and winter temperatures of −1–0 °C (Woś, 2010; data for 1951–2000). Over the last 70 years, the mean annual temperature oscillated between 8 and 9 °C, and the total annual precipitation was approximately 650–700 mm (Woś, 2010; Borycka and Kasprzyk, 2018). However, the total annual precipitation is highly variable in Poland, with an amplitude range of 650 mm in Rzeszów. The mean annual number of precipitation days is 160. Highest precipitation typically occurs from May to August (Woś, 2010; data for 1951–2000).

2.2. Aerobiological sampling

To identify potential spatial variability of the response of pollen concentration to rainfall, we conducted aerobiological monitoring using two Hirst volumetric traps located in the city centre (AS 1) and in the city suburbs (AS 2) (Fig. 1A) at 12 m a.g.l. (roof level). The distance between both stations was below 3 km that was not far in aerobiological sampling. The diurnal courses of airborne pollen of anemophilous plants in the stations located in such near distance are very similar (Borycka and Kasprzyk, 2018). This fact allow to noticed easily each differences between stations in hourly concentrations and conclude about local variability of meteorological conditions that might be a cause of this differences.

The detailed procedures for sampling, microscopic slide preparation, and scanning are described by Stach and Kasprzyk (2005). Pollen grains were counted at hourly intervals, and the units of the data were expressed as hourly and daily concentrations (pollen grains•m^{-3}). We identified four pollen types to the genus or family level in this study: *Betula, Pinus*, Poaceae, and *Urtica*. The high daily concentrations occurred during the warm months (April until the beginning of September). Their pollen grains differ in terms of size, weight, and aerodynamic properties (Frenguelli, 2015).

2.3. Meteorological data

Meteorological data were obtained from two stations: MS 1) Rzeszów-Jasionka located at the airport approximately 10 km from the city centre, and MS 2) located a few metres from AS 2 (Fig. 1A). We used two stations to determine potential spatial differences in daily precipitation variability and precipitation intensity in the city area. This

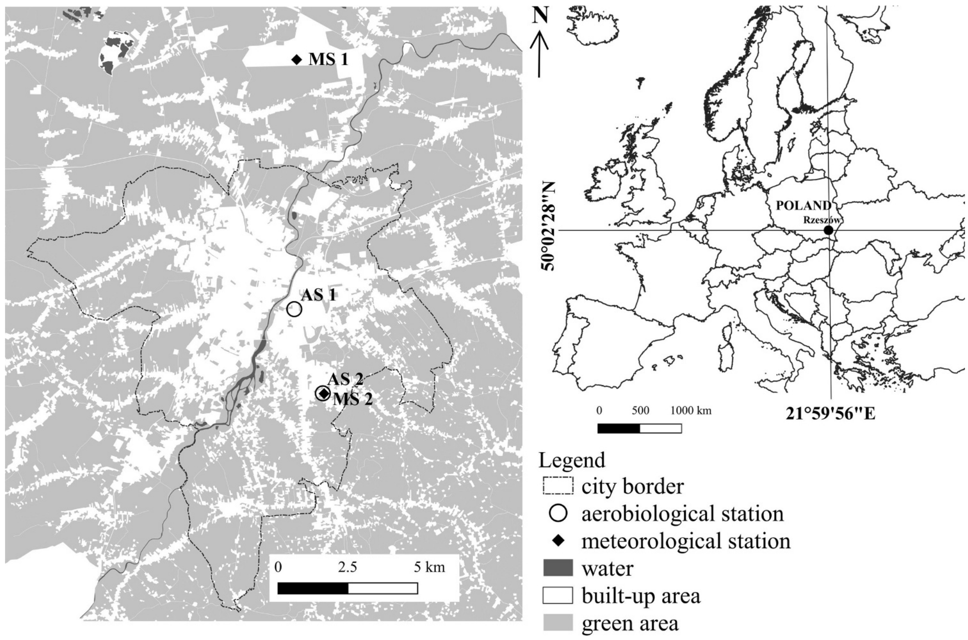

Fig. 1. Map of the study site, including A) the location of Rzeszów in Europe, and B) the location of aerobiological (AS1, AS2) and meteorological (MS1, MS2) stations in Rzeszów and the surrounding region over regional land-use .

is particularly necessary in the warm months (April–September), as rainfall is typically characterised by high local variability (Twardosz et al., 2011). We used hourly meteorological and synoptic records (from specialised observers) from MS 1. The data collected from MS 2 were recorded automatically at 10-minute intervals. We collected records of the following parameters: total precipitation (mm), average air temperature (℃), average relative air humidity (%), wind direction (°) and velocity ($m{\cdot}s^{-1}$), and sunshine duration (number of hours of sunlight). Importantly, 10 min of rainfall measurements were carried out simultaneously by two rain gauges. Therefore, it was possible to compare data and eliminate errors or gaps in values, which happens in this type of devices.

From MS 1, we also used data on cloud cover and cloud type. The synoptic meteorological situation was defined using synoptic maps and radar photos obtained from the Polish Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB, 2019) and the Deutscher Wetterdienst (DWD, 2019).

2.4. Data analysis

Further analysis was carried out on data from selected days of the year that fulfilled the following criteria:

1 First, we selected days in which the pollen concentrations were at least 100 pollen grains•m^{-3} to avoid the influence of random daily pollen grains distributions. The threshold 100 pollen grains•m^{-3} was independent of the pollen grain type.
2 From this group, we chose days in which daily sum of precipitation exceeded 0.1 mm.
3 We then selected the days, based on the sum of precipitation recorded every 10 min, in which precipitation commenced at the beginning of a full hour (e.g. 10.00) and lasted a minimum of 60 min. Only such assumptions give confidence that the concentration of pollen in a given hour could be affected by precipitation, which also had to last for an hour.

Therefore, in this type of research it is necessary to have meteorological measurements carried out in close proximity to the aerobiological station and at least every 10 min.

However, tracking precipitation at 10-minute intervals (MS 2) can provide more detailed information on precipitation intensity as well as the timing (beginning and the end) of precipitation events. We also tracked hourly pollen concentrations a few hours before and after the rainfall. A total of 81 days from 2016 to 2018 were included in the analysis of this study (26, 31, 24, respectively).

Selected days that met the above three criteria were then grouped. A hierarchical (agglomeration) method of cluster analysis, as well as a k-average method, was used in the paper. The grouping criteria take into account mainly the hourly rainfall sum and their percentages in each hour (taking 24-hours as 100%) and hourly pollen grains concentrations. This statistical method, used to group the values of variables and objects, is particularly useful in the analysis of many variables, just as in the case of used in our study. Objects which belong to the same group (cluster) are the most similar to one another.

In the study Pearson correlation coefficients between hourly pollen concentration and hourly values of selected meteorological elements were used. Correlations were determined in each of the separated groups and for all analysed days (Table 1).

3. Results

According to cluster analysis three groups differed in the timing of precipitations (night, morning (before noon), afternoon/evening) were distinguished. Another analysis allowed to distinguish three groups between three levels of precipitation intensity: light (<2.5 mm per hour), moderate (2.5–5.0 mm per hour), and heavy rainfall (>5.0 mm per hour). Two types of grouping were compiled and four clusters were obtained. K-average analysis confirmed the validity of this grouping scheme. Afterwards, the analysis of concentrations before, during and after precipitation were made. The last analysis indicated that distinguish of additional five group was adequate because of different concentrations course than described in group 2 (Table 1). The majority of cases analysed concerned *Urtica* pollen (47%), than *Betula* (21%) and Poaceae (20%) and the lower number of cases were for *Pinus* (12%). The division of days into five groups was independent of pollen types or the plant type (herbaceous and trees)- the herbaceous types included in all groups and trees in four groups.

Table 1
The characteristics of distinguished groups.

Characteristics	Group 1	Group 2	Group 3	Group 4	Group 5	All
number of cases	18 days (22%)	39 days (48%)	8 days (10%)	13 days (16%)	3 days (4%)	81 (100%)
time of occurrence (most often – %)	May-August (July 50%)	April-August (July 28%, May 25%)	April-July (July 62%)	April- August (April 38%, June 31%)	May-July (each 50%)	April-August (July 31%, May 21%)
pollen types	*Urtica* (83%), *Pinus* (17%)	*Urtica* (37%), *Betula* (28%), Poaceae (20%), *Pinus* (15%)	*Urtica* (50%), *Pinus* (25%), *Betula* (12,5%), Poaceae (12,5%)	*Betula* (38,5%), Poaceae (38,5%), *Urtica* (23%)	Poaceae (100%)	*Urtica* (47%), *Betula* (21%), Poaceae (20%), *Pinus* (12%),
precipitation characteristics	short-lived precipitation (about 60-minute) in the **afternoon** accompanied by thunderstorms	short-lived precipitation (about 60-minute) in the **afternoon** accompanied by thunderstorms	short-lived precipitation (about 60-minute) in the **morning** sometimes with accompanied by thunderstorms	**night-time** precipitation (from 2 to 10 hours)	short-lived precipitation (about 60-minute) in the **afternoon** accompanied by thunderstorms	Day with sum of precipitation >0,1 mm
intensity of precipitation	>5 mm•h^{-1} and/or >2 mm•10 minutes^{-1}	<2.5 mm•h^{-1} and/or <1 mm•10 minutes^{-1}	>2,0-5,0 mm•h^{-1} and/or >1 mm•10-minutes^{-1}	<2.5 mm•h^{-1} and/or <1 mm•10 minutes^{-1}	<2.5 mm•h^{-1} and/or <1 mm•10 minutes^{-1}	>0,1 mm•24 hours^{-1}
pollen concentrations	**rapid decrease** for few hours (5–6 hours) – in the evening and at night	slight effect on hourly pollen concentration (**slight decrease**)	**decrease** for few hours (2-3 hours), followed by rapid **growth** at noon and afternoon	**pollen concentrations at night** (prior to and following night-time rainfall) were **higher than day-time; rapid increases** in pollen **just before and during the first 1-3 hours of rainfall**	**sudden increases** in pollen concentrations **just before and during the first hour of rainfall**	days with the average daily pollen concentrations >100 pollen grains•m^{-3}
weather before, during or after precipitation	sunny and warm (≥20-25℃), with low cloud cover and low relative humidity (50–60% at noon)	Sunny or cloudy and warm (≥15-20℃), with low cloud cover and low relative humidity (50–60% at noon)	sunny or cloudy, warm or moderately warm (15-25℃) with low relative humidity early afternoon (50–70%)	decrease in relative air humidity at night despite the occurrence of precipitation and wind velocity of about 2 m•s^{-1}	clear or with little clouds morning, in afternoon strong wind gusts, turbulence and thunderstorm	change of weather conditions linked to usually the transition of an atmospheric front
Synoptic situation	thunderstorm, most often associated with the passage of the atmospheric front	thunderstorm, most often associated with the passage of the atmospheric front	low pressure system with atmospheric front	transition of a cold or warm atmospheric front	thunderstorm, most often associated with the passage of the atmospheric front	usually (65%) low pressure
Pearson correlation coefficients between hourly pollen concentrations and hourly values of selected meteorological elements						
Precipitation (mm)	**-0.116***	0.004	-0.016	-0.021	0.044	-0.023
Temperature (°C)	**0.534***	**-0.072***	**-0.363***	-0.081	**0.343***	**-0.095***
Humidity (%)	**-0.561***	**-0.189***	0.052	**-0.192***	-0.212	**-0.166***
Wind speed (m•s^{-1})	**0.420***	**0.232***	-0.050	-0.036	-0.084	**0.153***
Sunshine duration (hours)	**0.460***	**0.185***	-0.075	-0.033	0.043	**0.139***

* – statistically significant values at the level of 0.05

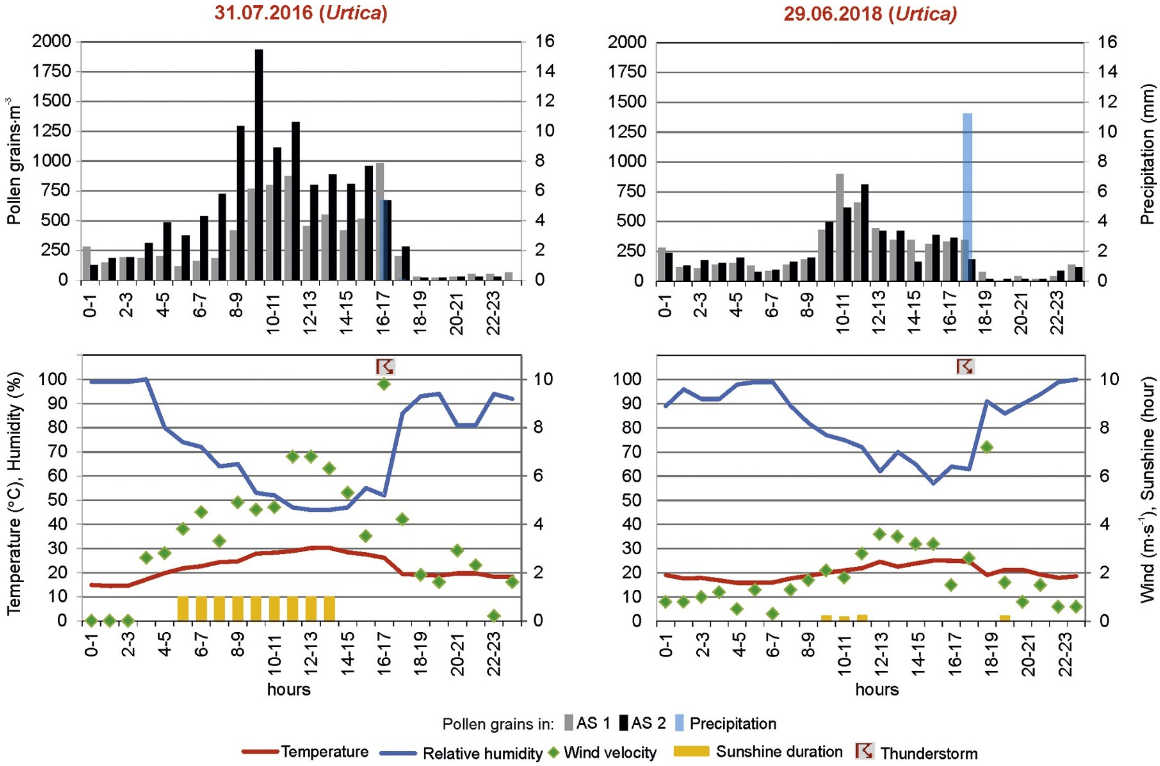

Fig. 2. Hourly course of atmospheric Urtica pollen concentrations and selected meteorological elements in Rzeszów on July 31, 2016 and June 29, 2018.

3.1. Group 1

The first group includes the days in which afternoon precipitation provoked a rapid decrease in hourly pollen concentrations. Hourly pollen concentrations were high a few hours before precipitation began (concentrations were hundreds or even thousands of pollen grains•m^{-3}). This situation occurred on 18 days, which is 22% of the total number of days studied and concerned mainly *Urtica* and also *Pinus* pollen concentrations.

Similar hourly patterns of *Urtica* pollen concentrations were observed on July 31, 2016 and June 29, 2018 (Fig 2). On these days (and the others included in the first group), the weather was influenced by a low pressure system. Precipitation was short-lived (60-minute) and began in the afternoon accompanied by thunderstorms. For all days in this group, pollen concentrations notably decreased when rainfall exceeded 5 mm•h^{-1}, with intensities greater than 2 mm in a 10-minute period. The decrease lasted a few hours (5–6 h), particularly in the evening and at night. During these days, the weather before the thunderstorm was sunny and warm (≥25°C), with low cloud cover and low relative humidity (50–60% at noon). These conditions increased rapidly during precipitation. However, on all days of this group, the hourly pollen concentration was affected by all meteorological elements included. The correlation coefficient values were very high and statistically significant (Table 1).

3.2. Group 2

The precipitation patterns in group 2 were similar to group 1. However, the total rainfall was lower in group 2 relative to group 1 at <2.5 mm•h^{-1} and <1 mm•10 min^{-1}. Group 2 harboured the largest number of days (39) at 48% of the total number of days analysed and included all four pollen studied.

Notable hourly *Urtica* pollen variability occurred on August 14, 2016 and August 2, 2018, in which precipitation only slightly influenced pollen concentrations (Fig. 3). Low and short-lived rainfall events were associated with thunderstorms in the early afternoon (13–16 UTC+2). The large differences in pollen concentration before and in the first few hours after rainfall between AS 1 and AS 2 may be due to the spatial variability of total precipitation between the two locations. Observed differences between MS 1 (3.0–5.0 mm in exemplary days) and MS 2 (0.7–0.8 mm) further confirms the spatial variability of precipitation intensity. A cold front with thunderstorm cells travelled from the north-west on August 14, 2016, whereas a thunderstorm within a tropical air mass travelled from the north-east on August 2, 2018. The timing of the thunderstorm (+/- 1 h) and total precipitation (+/- 3 mm) had differed between both days, and consequently the pattern of pollen concentration also differed in the following hours between the two aerobiological stations. Additionally, the diurnal changes in temperature, sunshine duration, degree of cloudiness, and cloud type were similar on both days. In contrast, we observed differences in relative air humidity and wind velocity during the night and in the morning. Lower night-time air humidity (70–80%) and wind velocities of >2 m•s^{-1} were the likely cause of higher pollen concentrations on August 14, 2016 relative to August 2, 2018. This is evidenced by the values of the correlation coefficient calculated for these days between the hourly pollen concentration and selected hourly values of meteorological elements at night and morning (22.00–9.00 UTC+2). They were higher on August 14, 2016 relative to August 2, 2018. They were respectively: air temperature: 0.947 and 0.695, relative humidity: −0.973 and −0.791, and wind speed: 0.900 and 0.853 (all statistically significant at 0.05).

To sum up, rainfall in this group of days only were slightly affect the decrease in pollen concentration. It also confirms the value of the correlation coefficient (0.004) of hourly pollen concentration and precipitation sums – not statistically significant (Table 1).

3.3. Group 3

The third group includes the days in which pollen grains were removed from the atmosphere (similar to the first group) following heavy rainfall (associated with thunderstorms or not), and where atmospheric pollen concentrations recovered rapidly 2–3 h later. These cases occurred in the hours before noon and were particularly rare, as summer

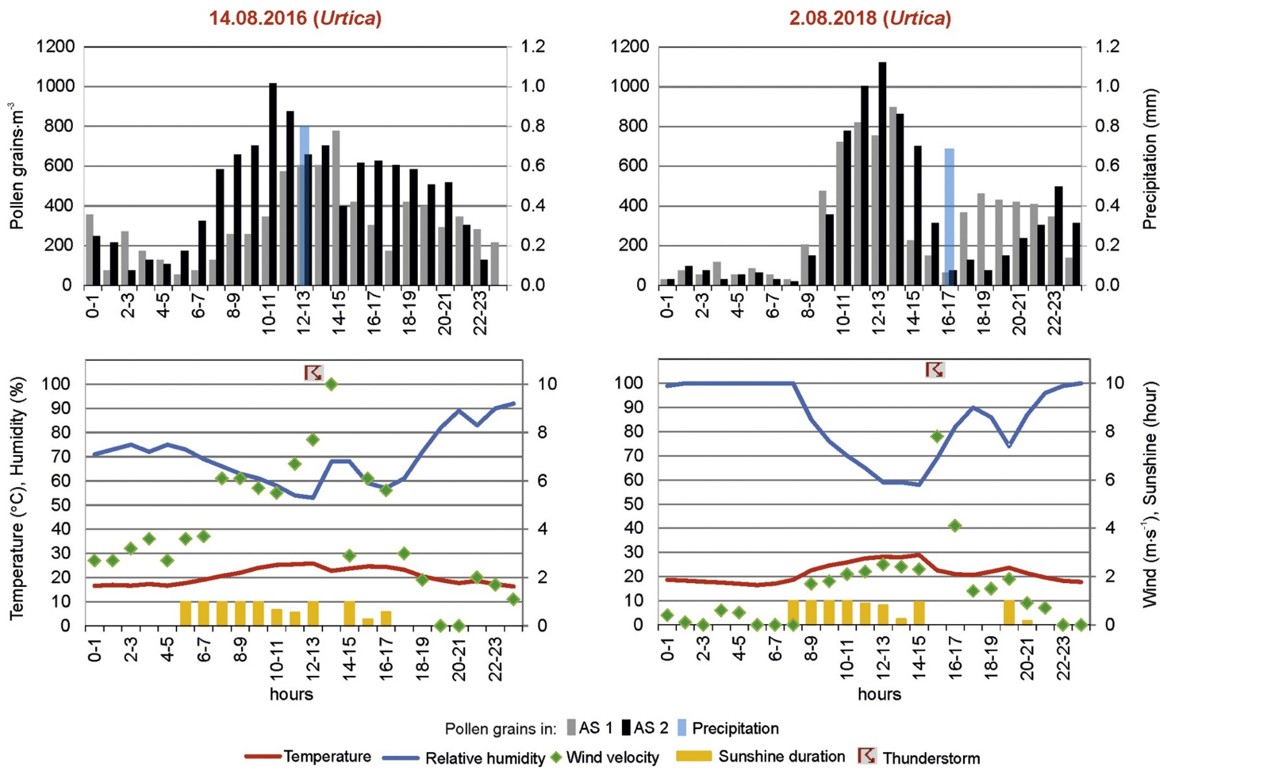

Fig. 3. Hourly course of atmospheric Urtica pollen concentrations and selected meteorological elements in Rzeszów on August 14, 2016 and August 2, 2018.

precipitation typically occurs in the afternoon. Only 8 days were categorised in this group, which is 10% of the total. The cases concerned mainly *Urtica* (50%) but also the rest three taxa.

For two of the days in this group (Fig. 4), rainfall occurred between 7 and 11 UTC+2, with an intensity of approximately 5 mm•h^{-1}. *Urtica* pollen concentrations were several times higher after 12 UTC+2 relative to before the precipitation event. The rate of increase in concentration varied between the two aerobiological stations due to spatial variability in rainfall intensity. On both days (July 8, 2018 and July 26, 2018), total rainfall was several times lower in MS 1 (1 mm) relative to MS 2 (above 8 and 10 mm) as the thunderstorm cell only partly covered MS 1. Further, air humidity and wind velocity largely influenced night-time pollen concentrations. Although we observed similar temperatures on both days (24.1 and 25.6℃) and nights (14.7 and 15.9℃), night-time *Urtica* pollen concentrations were lower on July 26, 2018 relative to July 8, 2018 (Fig. 4.) a few hours before rainfall. However, we observed lower relative air humidity (65–80%) and higher wind velocity (1.0 m•s^{-1}) on July 8, 2018, relative to July 26, 2018 (100% and 0.5 m•s^{-1}, respectively).

Days of moderate morning rainfall without the occurrence of thunderstorms (5 days) were also classified into this group (Fig. 5). On May 8, 2018, we observed low hourly pollen concentrations of *Pinus* until the early afternoon. The hours before noon were characterised by a lack of sunshine, high air humidity (up to 100%), and a rainfall intensity of 2.1 mm•h^{-1}. After 12.00 (UTC+2), air humidity decreased, the temperature and wind velocity increased, and sunshine was recorded. Hourly *Pinus* pollen concentrations began to increase rapidly and to a constant level of approximately 1000–1500 pollen grains•m^{-3}. Subsequent rainfall in the night-time hours gradually diluted atmospheric pollen concentrations. Correlation coefficient computed between hourly concentrations and meteorological parameters were not statistically significant in this group of days apart from correlation with temperature (Table 1.)

3.4. Group 4

Thirteen days were classified into the fourth group, which accounts for 16% of all days analysed (Table 1). This group is characterised by night-time precipitation (from 2 to 10 h) as well as high night-time pollen concentrations (just before and in the first 1–3 h of rainfall) (Fig. 6). The hourly pollen concentrations at night (prior to and following night-time rainfall) were higher than day-time concentrations. We observed rapid increases in pollen concentration immediately prior to, and in the first hour of, the rainfall event. The cases concerned three pollen types: *Betula*, Poaceae, *Urtica*.

These scenarios occurred in April 2016 and 2017 during the *Betula* tree pollination period. The following conditions accompanied observed increases in *Betula* pollen concentrations during rainfall events: 1) a rapid change of weather conditions linked to the transition of a cold (April 18, 2016) or warm (April 4, 2017) atmospheric front (Fig. 6); 2) a decrease in relative air humidity at night despite the occurrence of precipitation; 3) a minimum wind velocity of 2 m•s^{-1}; and 4) relatively low precipitation intensities of up to 1 mm•10 min^{-1} and up to 2.5 mm•h^{-1}.

One particular case was characterised by extremely high night-time concentrations of *Pinus* pollen grains on May 25/26, 2017 (Fig. 7). During the day (May 25), we observed very low hourly pollen concentrations (<100 pollen grains•m^{-3}) together with cloudy weather, a relative air humidity of >80%, and a moderate wind velocity of ~3 m•s^{-1}. These conditions were linked to the southern movement of a low pressure system and cold front over Rzeszów. The low intensity rainfall event occurred from 19.00 (UTC+2), with a total of 0.8 mm in the first hour. Interestingly, the following hour was characterised by an increase in atmospheric *Pinus* pollen concentrations. Between 21 and 24 (UTC+2), the hourly concentrations reached 940–4244 pollen grains•m^{-3}, despite the occurrence of intermittent and light rainfall (0.1–0.3 mm per 10 min). During precipitation wind velocity gradually decreased to ~1.0–0.5 m•s^{-1}.

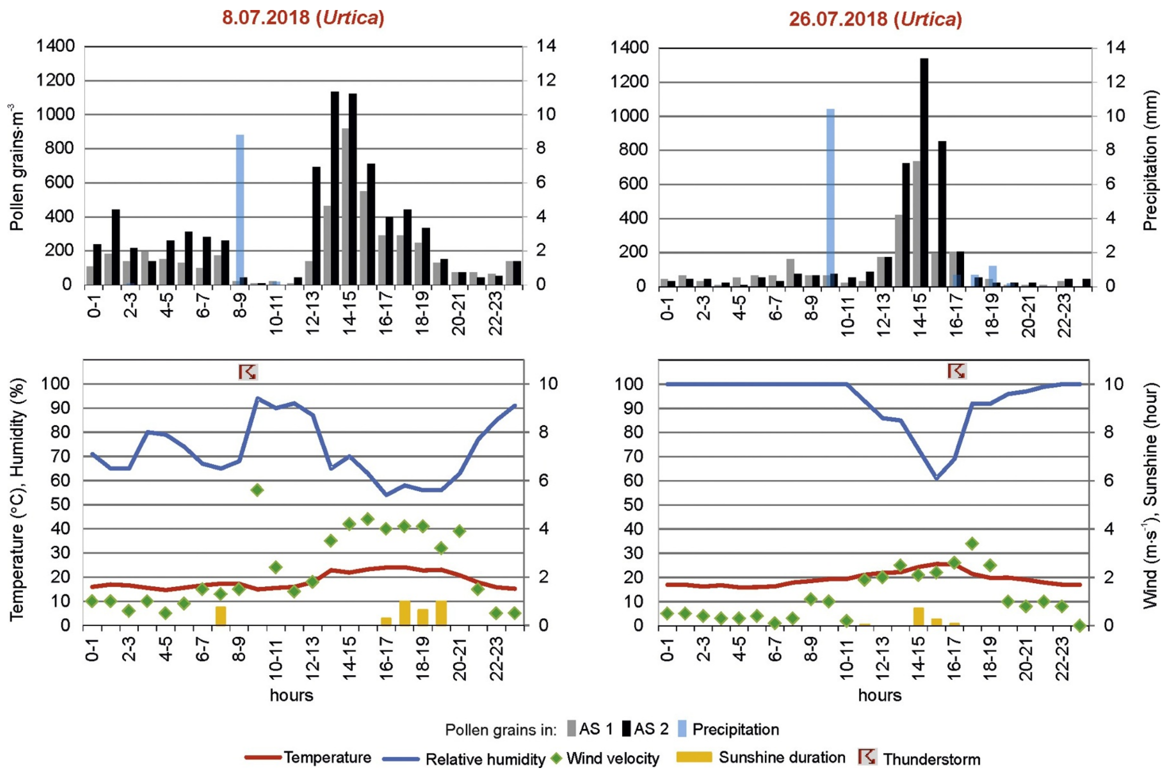

Fig. 4. Hourly course of atmospheric Urtica pollen concentrations and selected meteorological elements in Rzeszów on July 8, 2018 and July 26, 2018.

3.5. Group 5

The fifth group included the days in which increases in pollen concentrations occurred just before precipitation and during the first hour of rainfall event. The meteorological conditions on these days were similar to those in groups 1 and 2 (associated with thunderstorms) (Table 1). However, in contrast to group 1, sum of precipitation in hour was lower, it was the same as in the group 2. Throughout the 3-year period, this phenomenon occurred several times every year, but it was difficult to identify cases in which precipitation began at the beginning of a full hour. Therefore, group 5 only included 3 days (4% of the total days studied) and were associated with high Poaceae concentrations (Table 1).

An occluded front—related to a low pressure system centred over Slovakia—passed over Rzeszów on May 26, 2018 (Fig. 8). After a clear morning, thunderstorm cells over the surrounding city resulted in an increase in cloudiness and wind velocity (to about $3•s^{-1}$) from ~12 UTC + 2. Turbulence accompanied the thunderstorm cells, resulting in strong gusts of wind and moderate electrostatic discharges (atmospheric lightning). However, we observed sudden increases in Poaceae pollen concentrations from ~200–1200 pollen grains$•m^{-3}$ in AS 2 (13–14 UTC + 2) followed by pollen increases in AS 1 in the following hour (Fig. 8). This may be due to convection, turbulence, and descending currents underneath and behind the north-west moving Cu clouds. We did not observe downbursts in these cases, but wind velocity (Fig. 8) and wind gusts were strong. Rainfall began at 14 UTC + 2 in MS 2, with a maximum intensity of 1.2 mm$•10$ min^{-1} occurring between 14.30 and 14.40. At 14–15 UTC + 2, we observed an increase in pollen concentrations of up to 1544 pollen grains$•m^{-3}$ in AS 2 (near MS 2 where 10 min precipitation measurements were recorded). The concentrations decreased over the next few hours to pre-thunderstorm levels. The precipitation intensity of this group was similar to groups 2 and 4: rainfall was < 2.5 mm$•h^{-1}$ and only slightly over 1.0 mm$•10$ min^{-1} (1.2 mm$•10$ min^{-1} in this particular case). However, the washout effect had varied between the three groups.

4. Discussion

In examining the influence of meteorological parameters on airborne pollen concentrations, aerobiological studies have demonstrated that the total daily rainfall and/or the number of precipitation days had negatively correlated with pollen concentrations (Ribeiro et al., 2003; Alan et al., 2018; Bruffaerts et al., 2018). However, in many of these cases the correlations were weak. Common washout processes are driven by raindrops that attract airborne particles (such as pollen grains) by impaction, condensation, and nucleation (Gatz and Dingle, 1971 and references therein; Pérez et al., 2009). Studies which examined hourly correlations between meteorological parameters and pollen concentrations had excluded the potential impacts of rainfall (e.g. Ščevková et al., 2015). A few studies have focused on the detailed hourly variability of precipitation and its relationship with pollen concentrations (Norris-Hill and Emberlin, 1993; Borycka and Kasprzyk, 2018). In aerobiological studies, it is often recommended that precipitation days be excluded from analyses of diurnal pollen concentrations (Latałowa et al., 2005; Ščevková et al., 2015). In contrast, studies have inferred higher concentrations of pollen at the beginning of rainfall events (Norris-Hill and Emberlin, 1993; Borycka and Kasprzyk, 2018). In agreement, our three-year analysis demonstrated high daily pollen concentrations despite the occurrence of rainfall. For the taxa analysed in this study, previous studies have shown that the correlations between daily pollen concentrations and total daily rainfall were weaker (and at times showed no correlation) than the correlation of pollen concentrations with temperature (Ribeiro et al., 2003; Bruffaerts et al., 2018). This suggests that the pollen-precipitation relationship should be analysed not only in daily but also in the hourly intervals. It is particularly vital for pollen allergy sufferers following rainfall and thunderstorm events (Venables et al., 1997; Thien et al., 2018). It was also stated that significant positive relationship between airborne pollen concentrations sums and seed crop in a given year might exist for forest species like *Fagus* (Kasprzyk et al., 2014; Bogdziewicz et al., 2017). Similar finding were made for olive- the amount of pollen was positively related to the size of harvest (Minero et al., 1998). The knowledge about precipitation-pollen concentrations relationships could improve the models of crop forecasting

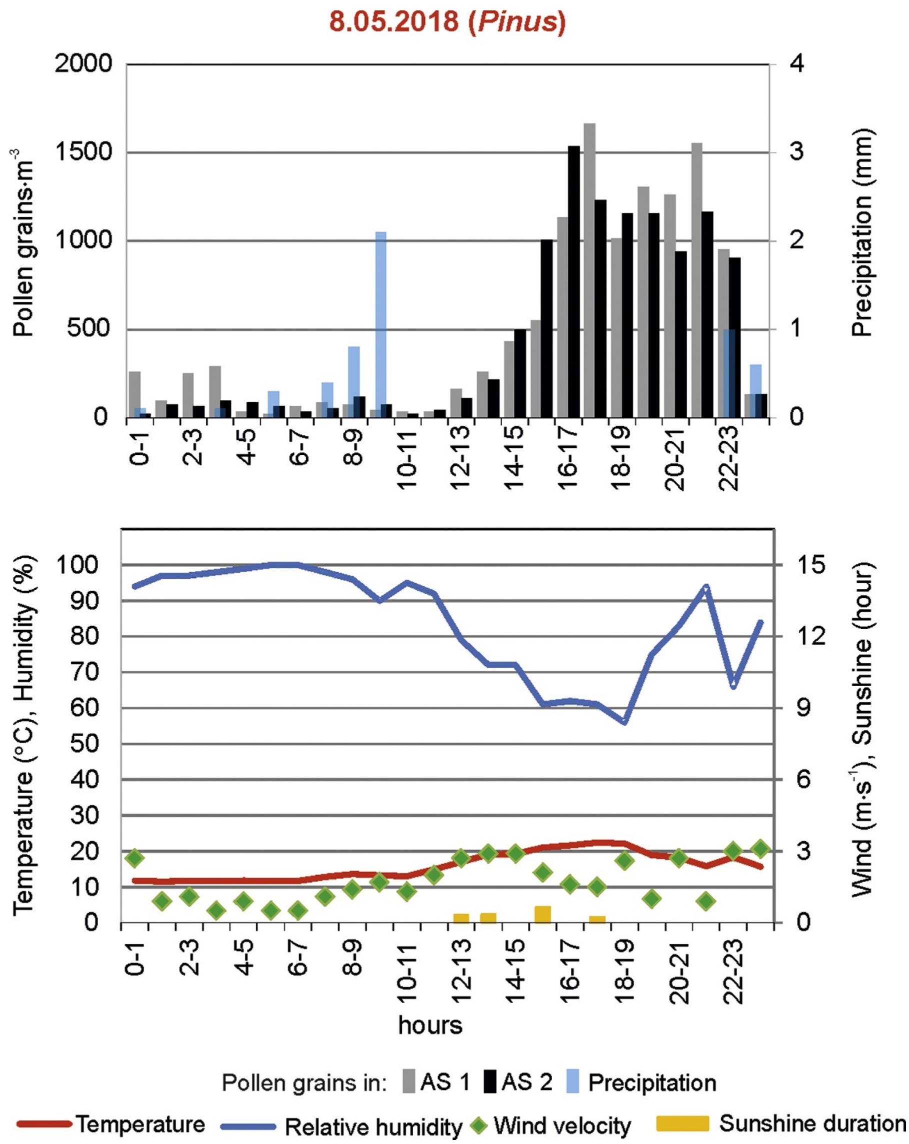

Fig. 5. Hourly course of atmospheric Pinus pollen concentrations and selected meteorological elements in Rzeszów on May 8, 2018.

(Minero et al., 1998). In such model different features of precipitation might be included: daily or monthly sums, intensity in different periods (i.e.: 10 min, hour, several hours), time of a day when pollen occurred-and detailed hourly analysis might be helpful in the choice of parameters that better fit the model. In this study, we distinguished three main responses of atmospheric pollen concentrations to precipitation events:

1) a decrease in concentration during rainfall events (groups 1 and 3),
2) no change or only slight decrease during and after rainfall events (group 2),
3) an increase in concentration just before and the in the first 1–3 h of rainfall (groups 4 and 5).

The relationships are likely influenced by a number of factors. We found that the response of pollen concentrations to precipitation was independent of taxa, despite the four pollen types having different aerodynamic properties (Frenguelli, 2015). Each of the three responses concerned the pollen grains of arboreal as well as herbaceous plants which differ in the height of pollen release. The majority of cases concerned *Urtica* and it was dominant in three of the five groups. However, this might be result of a fact that majority of cases occurred in July when *Urtica* pollen concentration are usually very high, even higher than Poaceae and *Betula* and *Pinus* pollen is absent. The group five included only Poaceae but it were only 3 days. Therefore, we could not conclude that this situation is characteristic only for grasses. It is probably linked with the rarely occurrence of short-lived precipitation in the morning.

According to our results, the time of day of precipitation events, precipitation intensity, and air humidity had influenced pollen concentrations. Afternoon rainfall either caused a decrease (group 1), a short-lived increase (group 5), or no influence (slight effect) on pollen concentrations (group 2). The type of response to afternoon rainfall was linked to rainfall intensity, which is discussed in the next paragraph. Morning rainfall events (group 3) were characterised by a decrease in pollen concentration and a rapid increase (for approximately four hours) after precipitation. This was mainly due to the increase in air temperature during the day. Correlations with other meteorological elements were not statistically significant. Generally, days in this group were characterized by both sunny and cloudy weather, but with higher air temperature (15–25 °C) and low relative humidity in the early afternoon (50–70%). Night-time precipitation (group 4) slightly influenced pollen concentrations or caused a clear increase during the event. Following the event, pollen concentrations continued to decrease for a few hours or even throughout the following day; the duration of

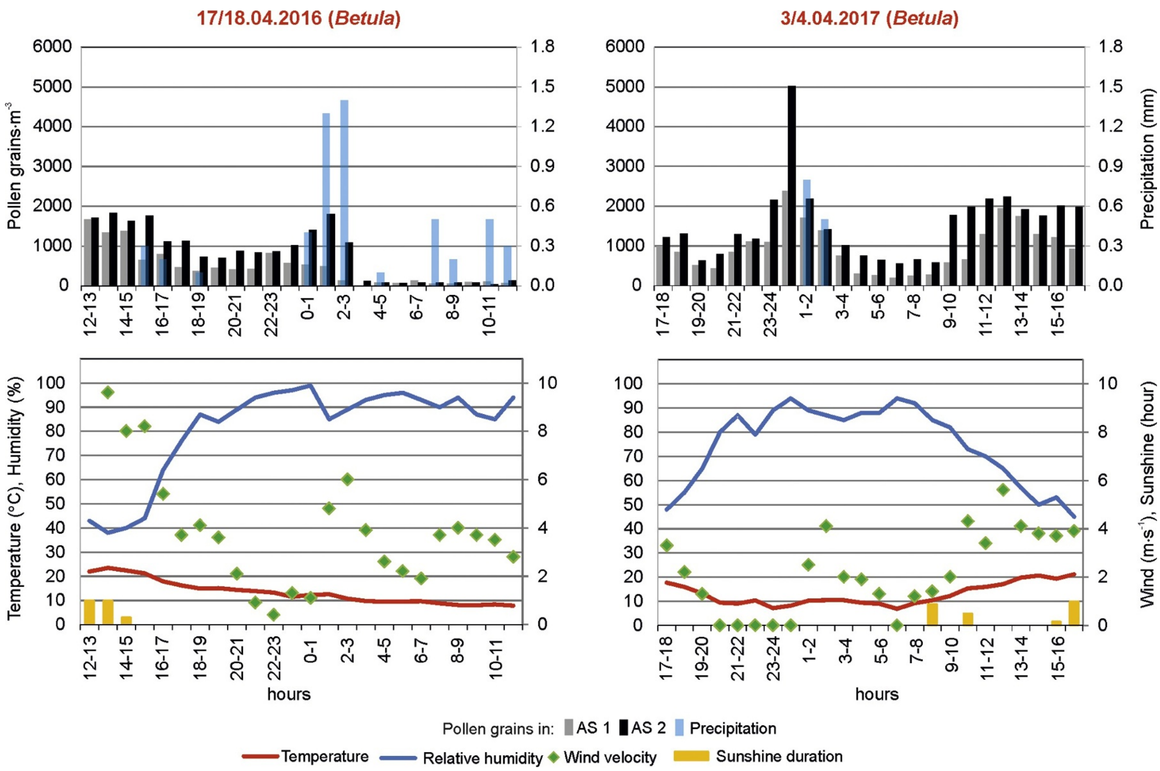

Fig 6. Hourly course of atmospheric Betula pollen concentrations and selected meteorological elements in Rzeszów on April 17/18, 2016 and April 3/4, 2017.

decrease was dependant on meteorological conditions. Most plants release pollen before or at midday, and thus, the absence of plant pollen emissions and persistently high levels of humidity following precipitation contribute to no chance to release the great amount of pollen once more during the day. However, morning rainfall likely has little influence on pollen concentrations emitted around midday, which is typically accompanied by a decrease in air humidity. In agreement, Wang et al. (2012) identified no significant variability in the diurnal course of pollen and/or allergenic particle concentrations when precipitation occurred before and after the time of pollen release.

However, the timing of pollen release does not directly reflect the diurnal patterns of atmospheric pollen concentrations. *Urtica* pollen concentrations were lowest during the early morning and during the night (Kasprzyk et al., 2001; Latałowa et al., 2005). *Betula, Pinus,* and Poaceae pollen concentrations were relatively homogeneous throughout the day (either without prominent peaks or with peaks occurring randomly throughout the day). Night-time peaks were common, particularly when low relative humidity and low wind speeds were recorded (Kasprzyk et al., 2001; Latałowa et al., 2005; Ščevková et al., 2015; Borycka and Kasprzyk, 2018). These diurnal patterns have been identified in studies that have excluded the impacts of precipitation. In our study morning rainfall likely delayed the increase in atmospheric all pollen types concentrations by a few hours (see example of *Urtica*). Concentrations increased within approximately four hours after precipitation. Afternoon rainfall of moderate and high intensity (group 1) caused earlier decreases in evening pollen concentrations. According the aerobiological research, rapid peaks (increases) in night-time pollen concentrations are common for *Betula, Pinus* and Poaceae in days without precipitation (Kasprzyk et al., 2001; Latałowa et al., 2005; Borycka and Kasprzyk, 2018), and precipitation may only disrupt *Urtica* pollen variability as described in group 4. Therefore, we claimed that rapid increase in night-time may be linked with meteorological conditions just before precipitation and thunderstorm (Norris-Hill and Emberlin, 1993) more often for *Urtica* than for other species. In cases where rainfall caused clear decreases in pollen concentrations (group 1 and 3), the degree of disruption to the diurnal pollen patterns was dependant on the meteorological conditions following the event (mainly air temperature), and the length of time before the next rainfall event occurred, such as the case presented in Fig. 6. Studies on the diurnal variability of pollen concentrations often identified strong negative relationships with hourly patterns in air humidity (Ščevková et al., 2015; Alan et al., 2018; Borycka and Kasprzyk, 2018; Bruffaerts et al., 2018). Our results confirm that in most groups the air temperature, and then the relative humidity is a dominant driver in the rates of increase of pollen concentrations following precipitation events.

In contrast to a number of studies regarding precipitation pollen scavenging (Gatz and Dingle, 1971; Pérez et al., 2009), we observed either an increase in pollen concentration within the first hour of rainfall or no impact of precipitation on pollen concentration in a number of cases in this study. The causes for this variability may be different. The majority of showers from Cb and Cu clouds are predominantly linked to thunderstorms, and increases in pollen concentrations may be due to strong wind gusts before and during thunderstorms (Venables et al., 1997; Thien et al., 2018). Strong wind can transport pollen loads to a number of surfaces (including leaf, roof, and ground surfaces) and can shake trees and herbaceous plants to release pollen from their anthers. This pollen can be deposited on tree catkins or other plant parts prior to precipitation events, which introduces new pollen to the atmosphere (Taylor et al., 2004; Kasprzyk and Borycka, 2019). Atmospheric pollen accumulation during precipitation events may also be due to the release of pollen prior to precipitation under conditions of low atmospheric pollen dilution. Olszowski (2016) suggested that atmospheric removal of the high PM_{10} concentration was more difficult under light (<0.5 mm•h^{-1}) and short-lived (<0.5 h) rainfall and low wind velocity (<0.5 m•s^{-1}). However, no significant differences in the effectiveness of washout was observed between locations of high or low PM_{10} concentrations when rainfall durations were >0.5 h and rainfall intensities were >0.5 m•h^{-1}. The pollen grains examined in this study are slightly larger than PM_{10} particles (average of 15–50 μm), and thus we would assume more rapid removal of these particles relative to the

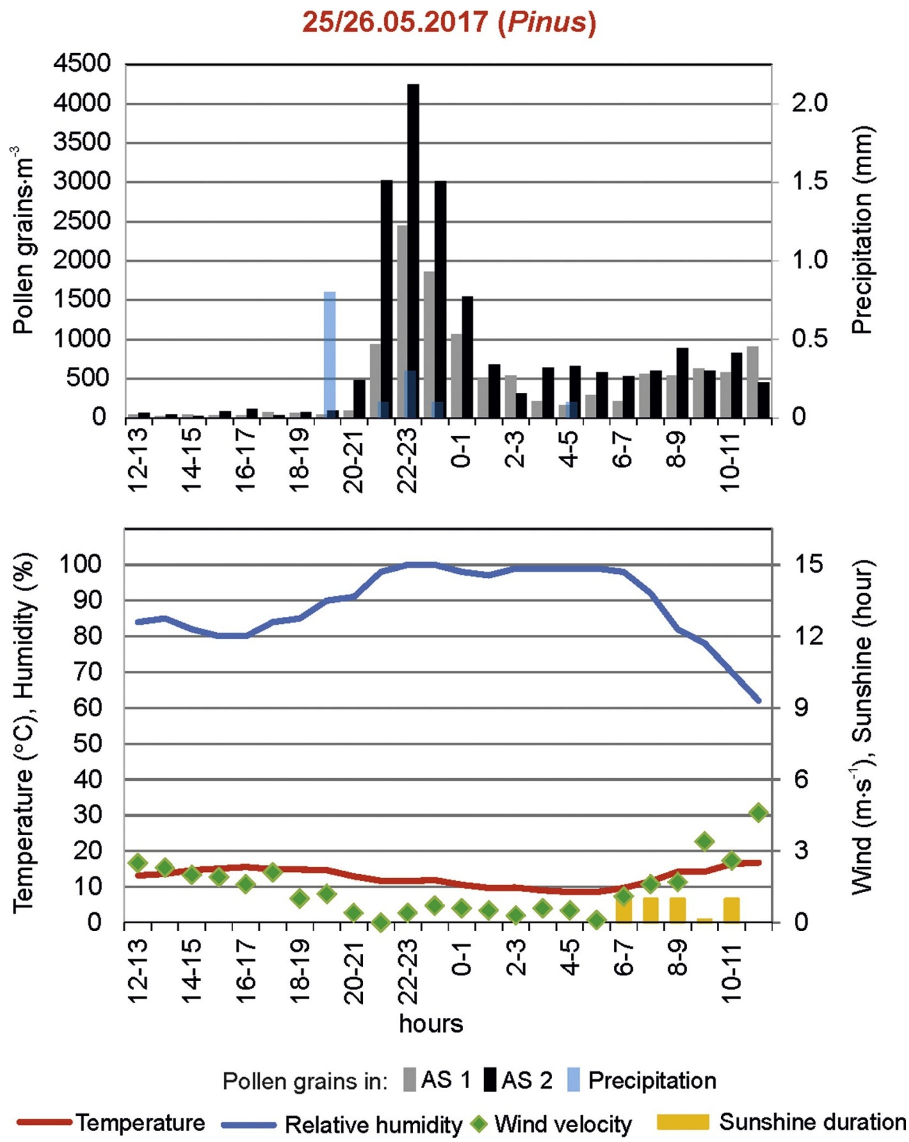

Fig. 7. Hourly course of atmospheric Pinus pollen concentrations and selected meteorological elements in Rzeszów on May 25/26, 2017.

smaller PM_{10} fraction (Norris-Hill and Emberlin, 1993). However, we did not observe rapid dilutions of high atmospheric concentrations of *Betula* pollen (see group 4), even under maximum rainfall of 2.5 mm•h^{-1}, likely due to low wind speeds of 2–4 m•s^{-1} or even 6 m•s^{-1} (as discussed previously). These observations suggest that the effectiveness of pollen washout may be linked to the plant phenophase and/or the phase of the pollen season. When plants reach peak pollination and the weather is warm and clear prior to a precipitation event (group 4), we observed an increase in pollen concentration during precipitation in both the night and day-time (such as Poaceae; group 5). The biology of pollination may also influence the magnitude of atmospheric pollen increase. *Betula* and *Pinus* shed a large amount of pollen during their relatively short (approximately 3–4 weeks) pollen seasons. In comparison, Poaceae and *Urtica* intermittently release small amounts of pollen over longer pollen seasons of approximately 4-5 months. As a result, the daily and hourly concentrations of arboreal taxa are much higher than herbaceous taxa. In this study, *Betula* and *Pinus* hourly pollen concentrations during precipitation were greater (2000–5000 pollen grains•m^3) than the concentrations of *Urtica* and Poaceae (up to 1600 pollen grains•m^3). High pollen concentrations during precipitation may also be facilitated by the transport of pollen by thermal currents to the upper atmosphere during the pollen seasons (Zhao et al., 2014). Due to the effect of impaction and condensation (Gatz and Dingle, 1971), pollen loads are subsequently transported to the lower atmosphere during precipitation events, causing temporary increases in atmospheric concentrations (Kasprzyk and Borycka, 2019). Pollen grains often occur as ice nuclei in clouds but are unlikely to be a large source of atmospheric pollen, as their concentrations are typically low (Tao et al., 2012). Gatz and Dingle (1971) claimed that larger rain drops in heavy rainfall events were less effective at atmospheric pollen removal relative to smaller drops of lower intensity rainfall due to their lower surface-to-volume ratio. Although the size of raindrops were not estimated in this study, we suggest that this parameter be considered in future analysis.

We observed notable decreases in pollen concentrations during precipitation intensities of approximately 5 mm•h^{-1} and >2 mm in a 10 min period (groups 1 and 3), which is classified as heavy (in this study) or moderate rainfall (Llsat, 2001; Monjo, 2016; Glossary of Meteorology, 2018). This observation confirms the assumption that higher intensity rainfall removes atmospheric particles more efficiently (Olszowski, 2016). We observed low pollen concentrations after heavy rainfall, which in some cases did not recover for four–five hours after the event. In contrast to our findings, Pérez et al. (2009) detected a clear decrease in pollen concentrations under maximum daily

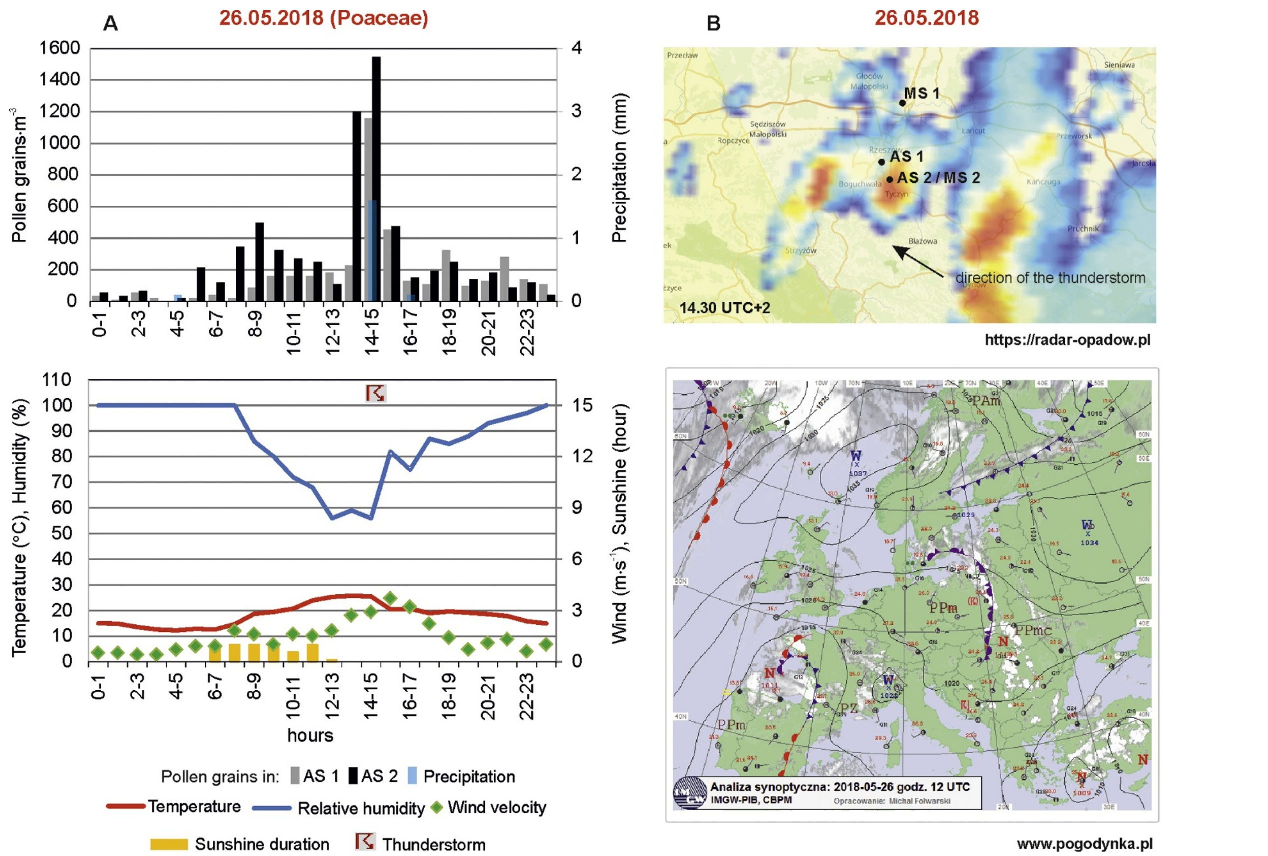

Fig. 8. A) Hourly course of atmospheric Poaceae pollen concentrations and selected meteorological elements in Rzeszów on May 26, 2018, and B) radar photo and synoptic map.

precipitation as low as 1 mm. They linked their observations to the wet deposition of particles during drizzle. This is in agreement with our findings of lower pollen concentrations during conditions of higher relative humidity and reduced rates of increase in pollen concentrations under high humidity following rainfall events (80–100%). However, we observed no decreases and some increases in concentration after rainfall of intensities $<1.0–2.5$ mm•h^{-1}. Low precipitation therefore induced no change in atmospheric pollen concentrations in this study. Pérez et al. (2009), observed low daily pollen concentrations when the daily maximum precipitation was as low as 1 mm and when high relative humidity persisted. Our findings show that if the around 1 mm precipitation occurred in less than 1 h period and air humidity is low during long time, no decrease in concentrations were noted. Therefore, the intensity as well as the type of precipitation should be considered. The study by Pérez et al. (2009) mainly focused on drizzle and not heavy rainfall (as is the case in this study). In addition to drizzle, snowfall has also been found to reduce atmospheric pollen concentrations. However, the increase pollen concentrations during continuous snowfall exceptionally occurred (Kasprzyk and Borycka, 2019). It is also worth noting that atmospheric pollen concentrations do not always correlate with the concentrations of other allergens in the respirable fraction. Although pollen concentrations during drizzle or heavy rainfall may decrease, research has shown that large amounts of allergenic particles are released from grains after exposure to precipitation (such as dew, fog, drizzle, or rainfall) (Taylor et al., 2004; Rathnayake et al., 2017).

In a number of cases, the removal of atmospheric pollen was rare in the first hour of a rainfall event as well as the following two hours. However, concentrations either rapidly increased or showed no change to previous concentrations during rainfall events. Similar patterns were observed in London (Norris-Hill and Emberlin, 1993), where pollen concentrations increased shortly before and during the first two hours of rainfall and was subsequently followed by a marked decreased thereafter. This short-lived increase was not attributed to wind speed. Our findings indicate the importance of wind velocity during such events, which may contribute to the rise in pollen concentrations. However, the high increase in pollen concentrations during very low (to 0.5 m•s^{-1}) occurred once (the situation of May 25/26, 2017). The trend of short-lived increase may also be due to the improved sampling efficiency of pollen traps by strong and rapid changes of wind speed (Emberlin, 2003). Previous studies have also identified increasing atmospheric pollen concentrations and other smaller allergenic particle concentrations under stronger wind speeds (Ščevková et al., 2015; Alan et al., 2018).

5. Conclusions

According to our results, we found that during days with rain, precipitation intensity was the dominant control on atmospheric pollen concentrations. Pollen concentrations decreased only under rainfall intensities of approximately 5 mm•h^{-1} and this value we recommended as threshold value for long lasting decrease of pollen concentrations in our region. However, the recovery time of atmospheric pollen concentrations following precipitation events primarily depended both on rainfall intensity, other meteorological conditions (including air temperature, relative humidity, or sunshine duration), and the time of day. It might also depend on biological factors such as the plant phenophase or the phase of a pollen season and that might be the subject of future studies. We supposed that the concentrations-precipitation relationship is independent of pollen type-taxa and the height of pollen release by herbaceous plant or tree. However, further studies are needed for other taxa, especially these of low dispersal ability (i.e.: *Platanus*). In conclusion, we suggest that precipitation days should be considered in future aerobiological studies due to the potentially large emissions of allergens released from pollen grains under rainfall as well as the importance of precipitation in forecasting models for forestry and agriculture. Specifically, we recommended the comparison of diurnal atmospheric pollen variability between precipitation and non-precipitation days. It is necessary to expand this analysis to other regions, climatic conditions, and other pollen grain types. To improve crop forecasting model for forestry, the research for hourly concentrations and precipitation intensity and time should be done for *Fagus* and *Quercus*. The variability in responses of pollen concentration to precipitation is a large problem in forecasts. However, in future forecasting models this issue should be taken into account. Future studies should therefore focus on the atmospheric concentrations of the pollen concentrations before, during, and after precipitation events of varying intensities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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