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ORIGINAL PAPER

The variability of pollen concentrations at two stations in the city of Wrocław in Poland

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Abstract The aim of the study was to investigate the variability of *Alnus* and *Corylus* pollen concentrations at two stations located in the city of Wrocław, Poland—one at the city centre and the other 4 km from the city centre. Our goal was to compare measurements from these stations in relation to meteorology and land cover. We used Spearman's correlation coefficient to investigate any dependence between meteorological factors and pollen concentration. Additionally, to check the relation between the direction of inflow of air masses and pollen concentration, we calculated the backward trajectories using the HYSPLIT model. The results have shown that despite the short distance between the stations, the characteristic of the pollen season is different for both stations (i.a. date of start and end of pollen season, duration of the season). The Spearman's correlation coefficient between relative humidity and air temperature and pollen concentration was found to be statistically significant. The backward trajectories calculated with HYSPLIT suggested a different origin of air masses between stations for high-concentration episodes in the case of *Alnus*. Our study has shown that analysis of meteorological conditions and influence of air transport into pollen concentration makes it possible to ascertain the reasons for differences in pollen level at these two stations, both of which are located in the same climatological domain. The study also shows that the aerobiological condition may change significantly over a short distance, which is a major challenge, for example, for pollen emission, transport, and concentration modelling.

Keywords Pollen · HYSPLIT · Meteorological conditions · Back-trajectories

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1 Introduction

Corylus (hazel) and *Alnus* (alder) are trees which release first pollen grains that are measured in the air of Poland each year (Puc and Kasprzyk 2013). According to research conducted by Rapiejko et al. (2007) in Poland, the first symptoms of allergy of sensitized people to these taxa appear in low concentrations of pollen: for hazel, the threshold value is 35 pollen grains per cubic meter of air (pollen grains m^{-3}) and for alder 45 pollen grains m^{-3}, whereas symptoms for all sensitized people are observed at slightly higher pollen concentration amounting to 80 pollen grains m^{-3} in the case of *Corylus* and 85 pollen grains m^{-3} in the case of *Alnus*.

It is estimated that 11.1% of Polish citizens suffer from hazel allergies. In the case of alder, this number is slightly higher, reaching 11.6% (Samoliński et al. 2014).

The pollen season strongly depends on meteorology (Puc 2007; Puc and Kasprzyk 2013; Sofiev et al. 2013; Malkiewicz et al. 2016; Dąbrowska-Zapart et al. 2018) as well as the type of land cover (Myszkowska et al. 2010; Charalampopoulos et al. 2018). Air temperature, humidity, wind speed and direction influence the length and intensity of pollen release and concentration in the air (Nowosad et al. 2015). Precipitation and humidity affect pollen release very strongly—and after reaching certain threshold values, these factors may totally suppress pollen release (Sofiev et al. 2013). According to Helbig et al. (2004), the threshold value for *Alnus* and *Corylus* pollen, for parameterization of emission flux for relative humidity, is 60%, while for parameterization of resuspension it is 85%. Above these values, emission is limited or completely stopped. Early flowering anemophilous trees to burst their anthers requires special meteorological conditions like high temperature, low humidity and moderate wind speed (Efstathiou et al. 2011).

The correlation between meteorological factors and pollen concentration has been investigated, for example, by Piotrowska-Weryszko (2013), Puc et al. (2015), Dąbrowska-Zapart et al. (2018) and Majeed et al. (2018). Malkiewicz et al. (2016) stated that with regard to the presence of *Alnus* and *Corylus* pollen in the air, the greatest influence has thermal factor. According to Dąbrowska-Zapart et al. (2018), except the temperature, their studies showed also a statistically significant correlation coefficient between the amount of alder pollen grains and the weather front type. Puc and Kasprzyk (2013) compared pollen concentration and the meteorology for two cities in Poland (Szczecin and Rzeszów). They found that variations between the cities can be large, especially at the start of the season wherein the shift of the start of the season between stations in year 2011 almost reached 31 days. These cities, however, represent different climatological regions—Szczecin is located close to the Baltic Sea, while Rzeszów is located c.a. 700 km SE of Szczecin, thus representing a more continental climate.

In this work, we focus on the *Alnus* and *Corylus* measurements gathered at two stations located in the city of Wrocław, SW Poland, at a distance of c.a. 4 km, thus representing similar climatological conditions. The main aim of this work is to study the variability of pollen concentrations within the city of Wrocław by comparing the measurements gathered from two pollen stations located in this city with the meteorological conditions and land cover. One site is located close to the city centre and surrounded by urban development, while the other is c.a. 3.7 km straight line from the strict city centre and surrounded by parks. Despite the minimal distance between the two sites, remarkable differences in concentrations and beginning/end of the pollen seasons have been described.

2 Materials and methods

2.1 Pollen concentration data

Pollen data were collected between 2013 and 2014 at two sites in Wrocław (Poland). The first station is located in the city centre, on the roof of the Institute of Geological Sciences, University of Wrocław (henceforth "City station", 51°6′59″N, 17°1′40″E) at a height of 20 m above ground level (Fig. 1). In the vicinity of the sampling site, there are dense urban built-up areas and scanty patches of greenery. From the south, the building is surrounded by an alley of plane trees, while several horse-chestnut trees and small birches grow to the north of the building (Malkiewicz et al. 2014).

The second sampler is located at the top of the 15-m-high tower at meteorological station of the Department of Climatology and Atmosphere Protection, University of Wrocław (henceforth, "Park station", 51°6′19″N, 17°5′20″E) (Fig. 1). Near the station (around the 150 m straight line) is the biggest park in Wrocław (Park Szczytnicki), with a number of different tree genera, including alder and hazel. Airborne pollen counts at both sampling sites were gathered using a Burkard 7-day volumetric pollen trap (Hirst 1952) and analysed following the recommendations of the International Association for Aerobiology (Galán et al. 2014). Pollen grains are counted under a light microscope with 400 magnifications along four longitudinal transects. The results were expressed as the number of pollen grains per m^3 of air as a daily mean value (pollen grains m^{-3}) (Galán et al.

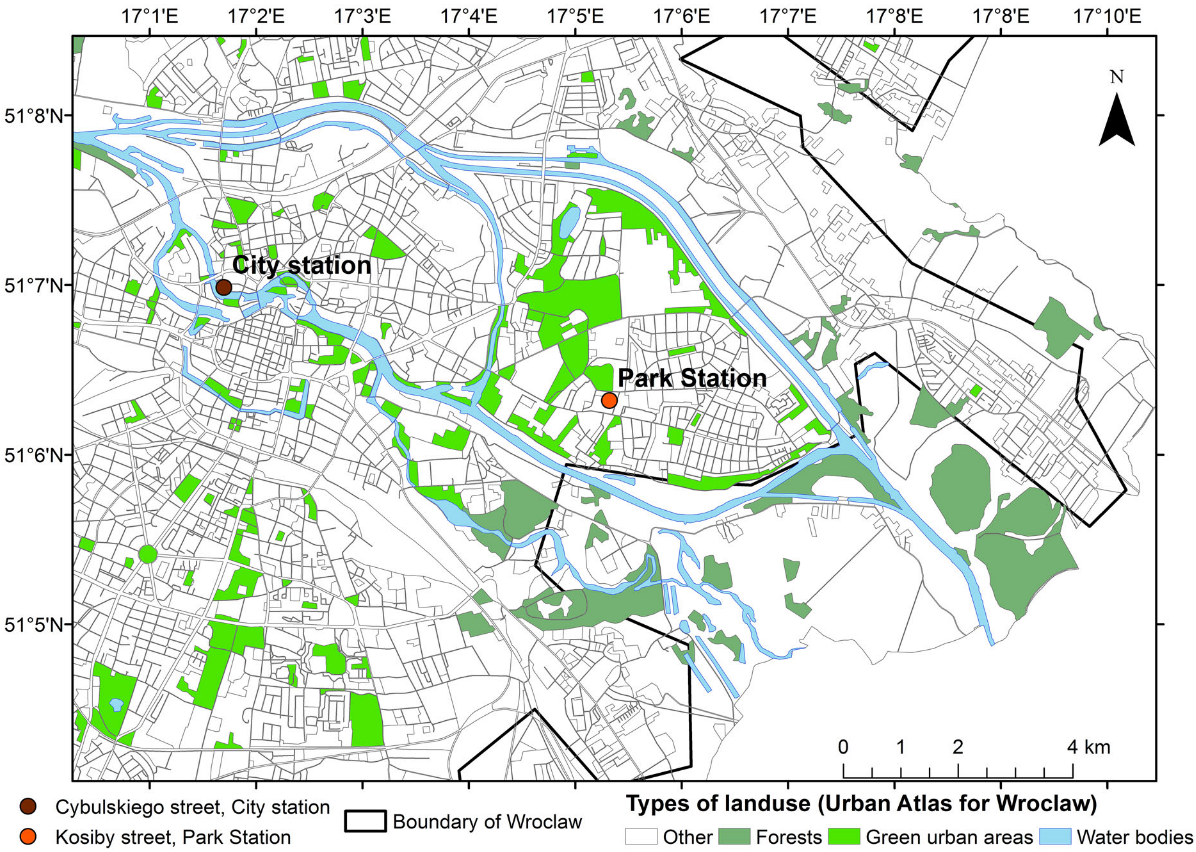

Fig. 1 Location and surrounding of two Wrocław stations—the City and the Park. Basemap—Urban Atlas 2012 (https://land.copernicus.eu/local/urban-atlas/urban-atlas-2012)

2017). Pollen concentrations of *Corylus* and *Alnus* are available for both stations for the years 2013 and 2014, and thus, these years were selected for further analysis. The start and end of the season were calculated using 95% method which means that the start and end day was when the sum of daily mean concentrations of pollen reaches 2.5% and 97.5%, respectively (Andersen 1991; Jato et al. 2006). The sum of daily pollen concentration during the whole season is here expressed as a Seasonal Pollen Integral (SPIn).

2.2 Meteorological data

Meteorological data were gathered at the Department of Climatology and Atmosphere Protection, University of Wrocław (51°6′19″N, 17°5′20″E), which included: mean [T (°C)], maximum [T_{max} (°C)] and minimum [T_{min} (°C)] temperature, mean and maximum relative humidity [RH, RH_{max} (%)], the sum of precipitation [R_{sum} (mm)], and daily mean and maximum intensity of precipitation [R, R_{max} (mm/h)], wind speed [V, (m s^{-1})], solar radiation [diffuse (SR_d) and total (SR_t)], and sunshine duration [SD (h)]. The distance of meteorological station is 5 m from the Park station and about 4 km straight line from the City station.

2.3 Statistical analysis

We have used the Spearman's correlation coefficient to investigate the relationship between pollen concentration and meteorological data. The pollen data for the whole season from the two sampling sites were correlated with meteorological data from the same day and from the previous day. RStudio Desktop 1.1.383 was used for the calculations (RStudio Team 2015). RStudio: Integrated Development for R. RStudio, Inc., Boston, http://www.rstudio.com/).

2.4 The HYSPLIT model

The Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) was created for i.a. diagnostic case studies or climatological analyses (Draxler and Hess 1998). Here, the HYSPLIT model was run in a trajectory mode. Meteorological data used for simulations were taken from the WRF model. The WRF model was configured with three nested domains having a spatial resolution of 12 km × 12 km that covered Europe, 4 km × 4 km (Poland), and 1.3 km × 1.3 km (SW Poland). Vertically, all the domains have 35 levels. GFS FNL data, available every 6 h, were used for meteorological initial and boundary conditions. Model configuration in terms of physical parameterization is provided by Kryza et al. (2017) and Ojrzyńska et al. (2017). For the HYSPLIT model, only the meteorological information from the innermost domain was used, as the high spatial and temporal resolutions were found to be important for the pollen transport studies, as reported earlier by Bilińska et al. (2017). The WRF model data were prepared for HYSPLIT using the arw2arl pre-processor.

The trajectories were calculated separately for the two sampling sites. We have used 72-h back-trajectories with a 2-h interval at two different altitudes (50 m and 1500 m agl). The trajectories were calculated for the years 2013 and 2014 for the whole pollen season of *Corylus* and *Alnus* and for pollen peaks as well. Apart from summarizing the entire pollen season, two kinds of grouping of high pollen concentration of *Alnus* were made. The first type ("high" group) covers days with the pollen concentration above 85 pollen grains m^{-3}, which is a threshold value for the occurrence of allergy symptoms for all sensitized people with respect to alder (Rapiejko et al. 2007). The second type ("peak" group) reflects days with peaks of pollen concentration. Peak days were selected with the function "findPeaks" from the R statistical package, with a threshold value equalling to 85 pollen grains m^{-3} for *Alnus*. For *Corylus*, we found no days where the threshold value for all allergic people of 80 pollen grains m^{-3} was exceeded at both stations, and therefore, only the whole season is analysed further. For alder, both the "high" group and "peak" group were analysed.

The next step was to create frequency maps of trajectories in each grid cell. These maps were prepared for the two genera in both locations for 50 m and 1500 m in 2013 and 2014. The frequency was counted as the number of trajectories in each grid cell divided by the total number of trajectories. Maps were created with the use of ESRI ArcGIS 10.2.2 and the R statistical package. The correlation coefficient was used to quantify the differences between the spatial patterns of trajectories' frequency between the two measuring sites. The correlation was calculated by comparing each spatially corresponding grid (for the entire domain—SW Poland, 282 × 222 grids) as proposed by Kryza et al. (2011).

The maps of trajectories frequency were presented with the land cover map as a background, showing spatial distribution of *Alnus* and *Corylus* species (qualitative information provided after Bińkowska et al. 2013).

3 Results

3.1 Corylus

3.1.1 Pollen season

During the analysed period, higher concentrations of *Corylus* pollen were observed at the Park station. At this sampling site, the start and end of the season were observed earlier than at the City station. The differences were especially large in year 2013. At the Park station in 2013, the season started 25 days earlier than at the City station and also finished 5 days earlier. In 2014, it was 12 and 6 days, respectively. The duration of the seasons varied according to the years—the longest season was observed in 2013 at the Park station (71 days), while the shortest was at the City station in 2014 which lasted 46 days. The Seasonal Pollen Integral was at least two times higher at the Park station compared to the City station, with the highest value reached in 2014 (2292 pollen grains m^{-3}). The highest maximum daily pollen concentration was measured in 2014 at the Park station (227 pollen grains m^{-3}, 13 February) (Table 1).

The distribution of *Corylus* pollen shows strong day-to-day variability over the pollen season (Fig. 2). The peak values are higher at the Park station, which is located close to the pollen sources. Figure 2 shows that the main peaks occur at the same time for both stations. There is also a strong correlation in temporal

Table 1 Characteristic of Corylus pollen season

	Park station		City station	
	2013	2014	2013	2014
Seasonal Pollen Integral (SPIn)	1031	2292	774	559
The start of pollen season	05.02	19.01	02.03	31.01
The end of pollen season	16.04	11.03	21.04	17.03
Duration of pollen season (days)	71	52	51	46
Maximum pollen concentration (grains m^{-3} air)/date	148	227	96	39
	06.03	13.02	06.03	15.02

variations of pollen concentrations between the stations, reaching 0.78 and 0.88 for the year 2014 and 2013, respectively.

3.1.2 Correlation coefficients between pollen concentrations and meteorological parameters

The correlation coefficients between *Corylus* pollen and meteorological parameters as measured on the same day are statistically significant for all parameters except for those from T_{max} and T in the year 2013 at the Park station. In the same year for the City station, the correlation was non-significant for T_{max} and T, V and SR_d. The highest negative significant correlation was calculated for RH (− 0.71) at the Park station. In 2014, the correlation between pollen concentrations and relative humidity was lower than that in 2013. At the Park station, the highest significant correlation was observed for T_{max} (0.58) and RH (− 0.52). At the City station, a positive correlation was calculated between pollen concentrations and T_{min}, RH_{max} and SD, and these correlations were statistically significant (Table 2).

The Spearman's correlation coefficient for pollen concentrations and several meteorological parameters from the previous day are significant for the year 2013. In that year, the highest negative coefficient for the Park station was for RH (− 0.56). For the City station, it was for T_{min} (− 0.57). In 2013, a high positive correlation reached SD (0.45) and SR_t (0.43) at the Park station. In 2014, the number of significant correlated parameters was lower than that in 2013. At the Park station in 2014, a significant correlation was shown for T (0.34) and T_{max} (0.45), RH (− 0.29) and SR_t (0.3) and SR_d (0.33). At the City station, only RH_{max} was significantly correlated with *Corylus* concentrations (0.44) (Table 3).

3.1.3 Back-trajectories analysis with the HYSPLIT model

In 2013, the differences between the directions of air masses' inflow were seen at different heights. At height 50 m, the inflow was mainly from the northwest, north-east, and south-east for both City and Park stations. With the increase in the altitude of trajectories at 1500 m, the inflow was dominant from the western direction for both City and Park stations, and with little contribution from the northern, eastern, southern, and south-western directions (Fig. 3). At all altitudes, trajectories crossed the area at which *Corylus* shrubs are observed. The correlation coefficient between the maps of trajectories' frequency for the City and the Park stations did not exceed 0.48 (p value $< 2.2e{-}16$) and decreased with increasing height of trajectories.

During the whole 2014 *Corylus* pollen season, the inflow of air masses was mainly from the southwestern, southern, and south-eastern directions. For the Park station, the frequency of the inflow from south-eastern direction was more noticeable than for the City station. At a height of 1500 m agl, the contribution of western and south-western directions was dominant. For the City station, the inflow was more dispersed than for the Park station (Fig. 4). The correlation coefficient between the maps of trajectories' frequency for the City and the Park stations did not exceed 0.44 (p value $< 2.2e{-}16$) and decreased with increasing height of trajectories.

3.2 Alnus

3.2.1 Pollen season

In the case of *Alnus,* differences at the start and end of the season between the sampling sites were smaller—

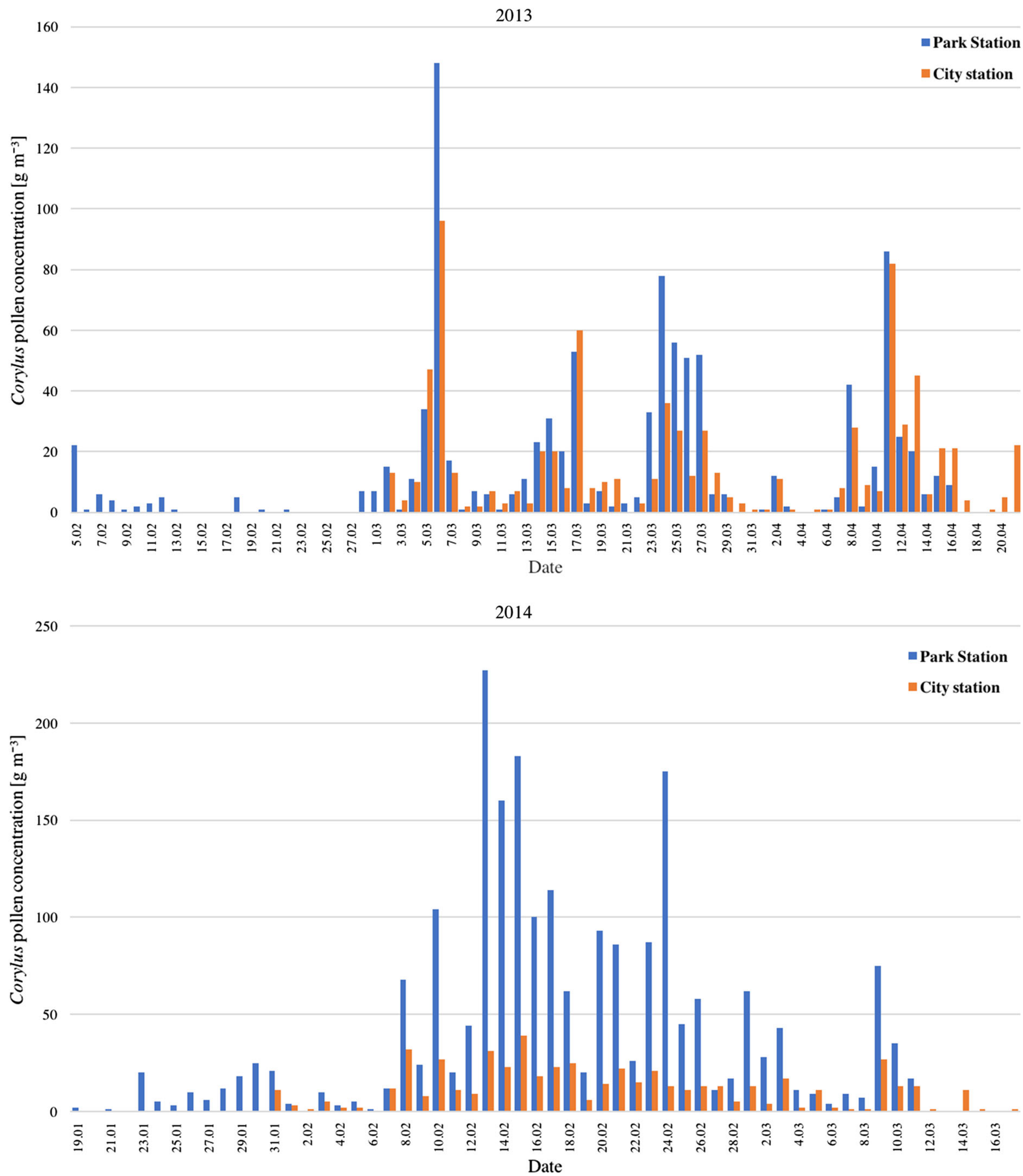

Fig. 2 Distribution of Corylus pollen in 2013 and 2014 for the Park station and the City station

Table 2 Spearman's correlation coefficient for Corylus pollen and meteorological data from the same day

	Park station		City station	
	2013	2014	2013	2014
T	− 0.10	**0.44**	− 0.05	0.00
T_{max}	0.06	**0.58**	0.12	0.19
T_{min}	− **0.42**	− 0.03	− **0.49**	− **0.31**
RH	− **0.71**	− **0.52**	− **0.62**	− 0.19
RH_{max}	− **0.53**	0.26	− **0.39**	**0.31**
R_{sum}	− **0.52**	− **0.28**	− **0.53**	− 0.18
R	− **0.45**	− **0.31**	− **0.54**	− 0.22
R_{max}	− **0.42**	− **0.29**	− **0.52**	− 0.22
V	**0.39**	− 0.07	0.26	0.04
SD	**0.55**	**0.41**	**0.51**	**0.30**
SR_t	**0.64**	**0.50**	**0.61**	0.14
SR_d	**0.26**	0.26	0.07	− 0.04

Bold—statistically significant (p value < 0.05)

Table 3 Spearman's correlation coefficient for Corylus pollen and meteorological data from the previous day

	Park station		City station	
	2013	2014	2013	2014
T_{max}	− 0.01	**0.45**	− 0.23	0.03
T_{min}	− **0.38**	0.00	− **0.57**	− 0.16
T	− 0.14	**0.34**	− **0.31**	− 0.10
RH	− **0.56**	− **0.29**	− **0.39**	0.16
RH_{max}	− **0.39**	0.22	− 0.26	**0.44**
R_{sum}	− **0.41**	0.17	− **0.46**	− 0.02
R_{max}	− **0.31**	0.14	− **0.36**	0.05
R	− **0.32**	− 0.15	− **0.37**	0.04
V	**0.28**	− 0.20	0.05	0.00
SD	**0.45**	0.21	**0.33**	0.09
SR_t	**0.43**	**0.30**	**0.31**	− 0.05
SR_d	− 0.13	**0.33**	− 0.13	0.13

Bold—statistically significant

the maximum shift did not exceed 1 day, and the season started earlier at the City station. The SPIn was highest in 2014 at the Park station (9846 pollen grains m^{-3}) and lowest in 2013 also at the Park station (2541 pollen grains m^{-3}). The duration of the pollen season varied from 29 days in 2014 at the Park station to 48 days in 2013 at the City station. The highest daily pollen concentration was measured in 2014 at the Park station (1853 pollen grains m^{-3}, 9 March) (Table 4).

The temporal distribution of *Alnus* pollen during the analysed 2 years was similar at both stations (Park and City). There was only one main peak observed for each year. The amount of pollen was similar at both Park and the City stations (Fig. 5). The correlation coefficient of pollen concentration between sites reached 0.94 (p value < 0.01) in 2013 and 0.91 in 2014 (p value < 0.01).

3.2.2 *Correlation coefficients between pollen concentrations and meteorological parameters*

With regard to *Alnus* pollen, for meteorological data from the same day as pollen data, the highest negative Spearman's correlation coefficient was for RH (− 0.65) at the Park station in 2013. For the same station and in the same year, the highest positive correlation was 0.60 for the total SR_t. For the Park station in 2014, the significant correlation was for T_{min}, T_{max}, RH_{max}, SD, SR_t, and SR_d. For the City station in the same year, T_{max}, RH_{max}, and SD were correlated positively with *Alnus* pollen concentrations. A negative correlation was observed for R_{sum} (Table 5).

The Spearman's correlation coefficient for *Alnus* pollen and meteorological data from the previous day in the case of the Park station for 2013 was significant for RH_{max} (− 0.45), RH (− 0.57), R_{sum} (− 0.53), R_{max} (− 0.33), R (− 0.37), SD (0.39), and SR_t (0.47). At the City station, the correlation was lower, reaching − 0.44 for RH and RH_{max}, − 0.46 for R_{sum}, 0.30 for SD, and 0.38 for SR_t. In 2014 at the Park station, a significant correlation was observed for T_{max} (0.39) and SR_t (0.4). For the City station, a positive correlation was observed for SD (0.38) (Table 6).

3.2.3 *Back-trajectories analysis with the HYSPLIT model*

During the whole *Alnus* pollen season in 2013, the direction of the inflow of air masses differed at different heights. At 50 m, it was mainly from north-eastern, south-eastern, and north-western directions

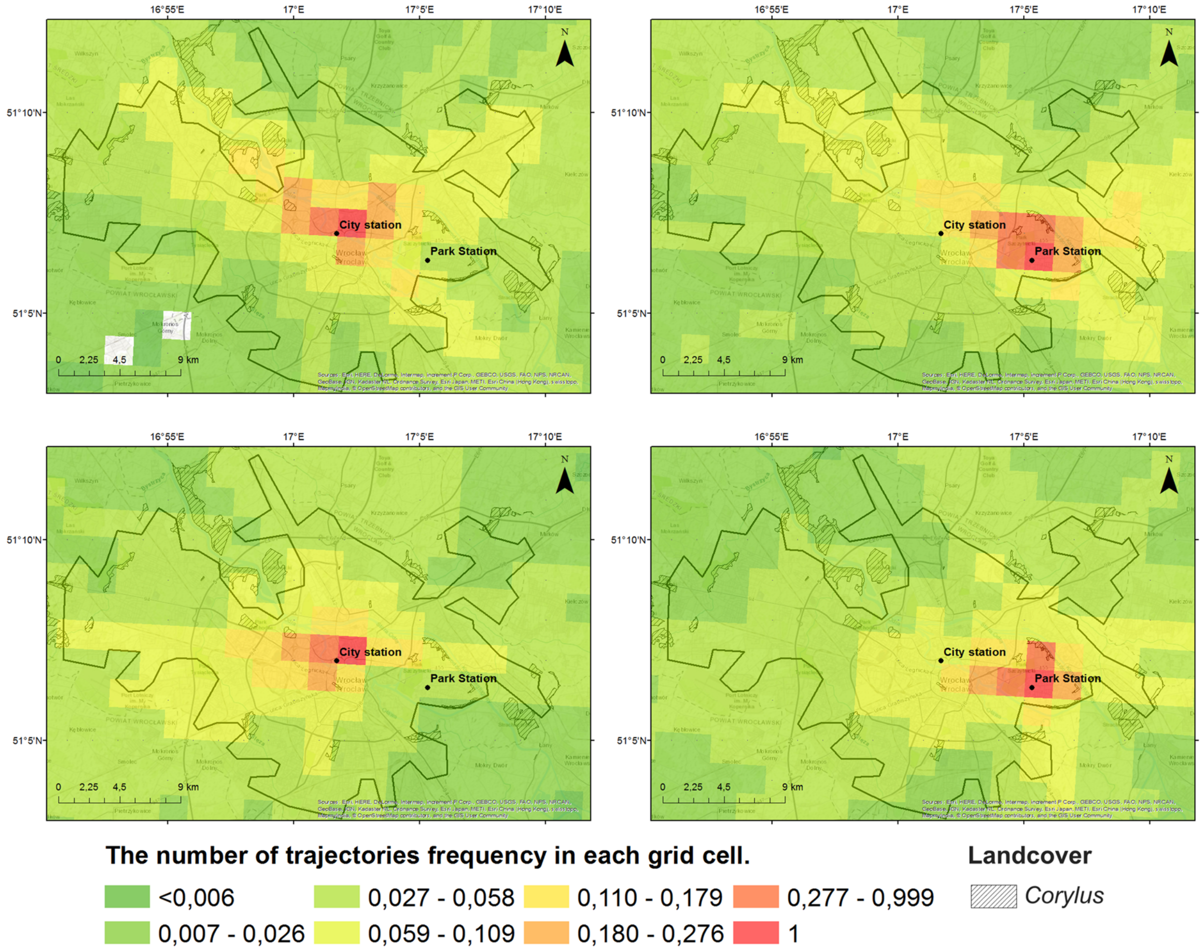

Fig. 3 Trajectories' frequency in each grid cell for the Corylus season in 2013 for the City station (left side) and the Park station (right side), for 50 m and 1500 m agl. (From top to bottom row)

for both City and Park stations. At 1500 m, the inflow of air masses was mainly from the western direction, but with contribution from northern, eastern, and south-eastern directions (Fig. 6). At both altitudes, the trajectories crossed the areas with the presence of *Alnus* trees. The correlation coefficient between the maps of trajectories' frequency for both City and Park stations did not exceed 0.43 (p value $< 2.2e-16$) and decreased with increasing height of trajectories.

For the "high" group (i.e. days with *Alnus* pollen concentration above 85 pollen grains m^{-3}), for the City station, the inflow of air masses at 50 m was from the southern and south-eastern directions, but with little contribution of air masses from the north-western direction. For the Park station, the advection was seen from the south-western direction, but with little contribution from the western direction. At 1500 m, the direction of air masses inflow in case of the City station was also more scattered than at the Park station. The main directions of air masses inflow were from the western and south-western directions, with contribution from the northern and north-western directions. In the case of the Park station, the inflow was mainly from south-western and western directions but with contribution from the south and north-west (Fig. 7). The areas with the presence of *Alnus* trees were crossed at both trajectories' height. The correlation coefficient between the maps of trajectories'

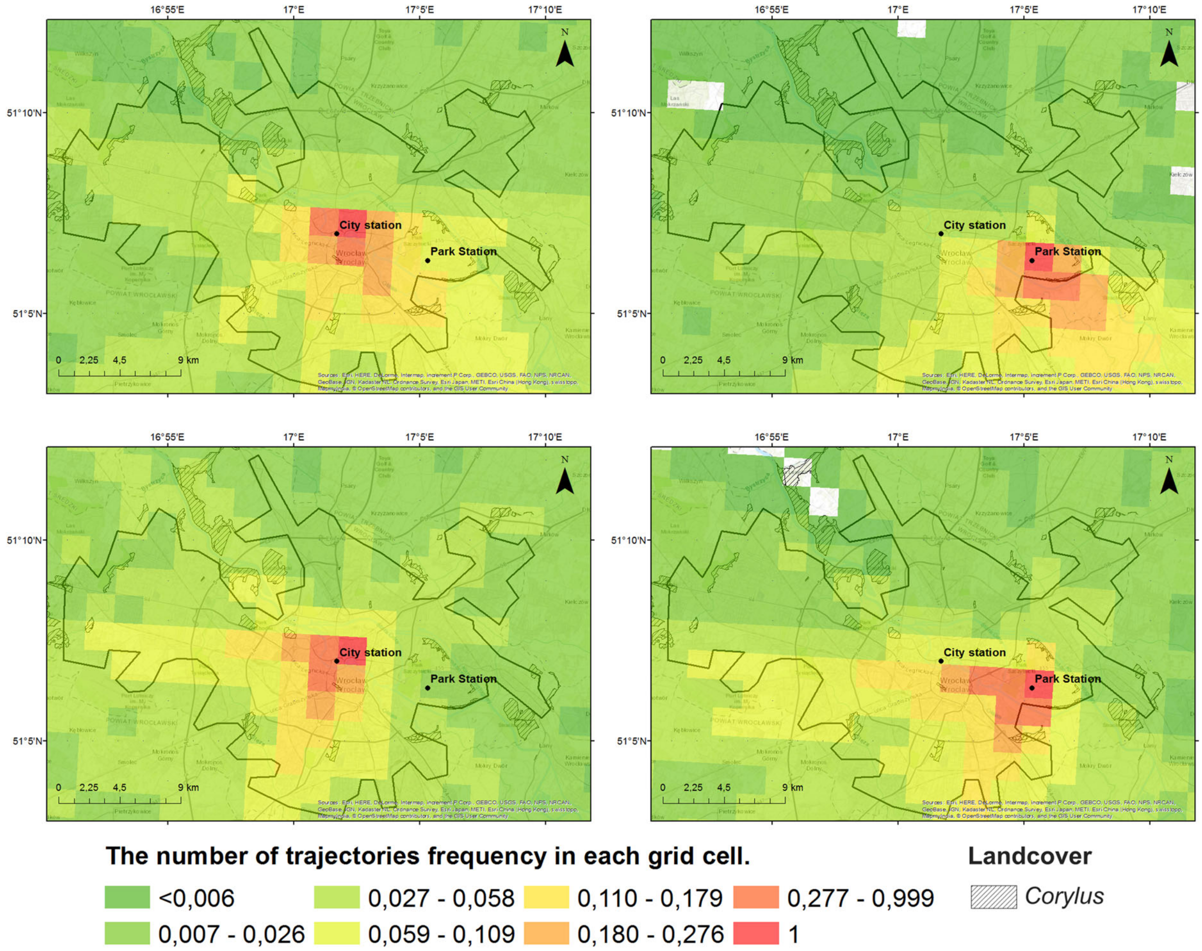

Fig. 4 Trajectories' frequency in each grid cell for the Corylus season in 2014 for the City station (left side) and the Park station (right side), for 50 m and 1500 m agl. (From top to bottom row)

Table 4 Characteristic of Alnus pollen season

	Park station		City station	
	2013	2014	2013	2014
Seasonal Pollen Integral (SPIn)	2541	9846	4638	4575
The start of pollen season	06.03	11.02	05.03	10.02
The end of pollen season	21.04	11.03	21.04	14.03
Duration of pollen season (days)	47	29	48	33
Maximum pollen concentration (grains/m^3 air)/date	800	1853	881	785
	11.04	09.03	11.04	09.03

frequency for the City and Park stations changed with altitude; at 50 m, it reached 0.23, and at 1500 m, it was 0.24 (p value $< 2.2e-16$).

For "peak" group in 2013, the inflow of air masses at 50 m for both stations was mainly from the south. At 1500 m, there was a noticeably larger participation from the south-western direction in the case of both stations (Fig. 8). During "peak" group, the air masses flowed over the areas with the presence of the *Alnus* trees. The correlation coefficient between the maps of

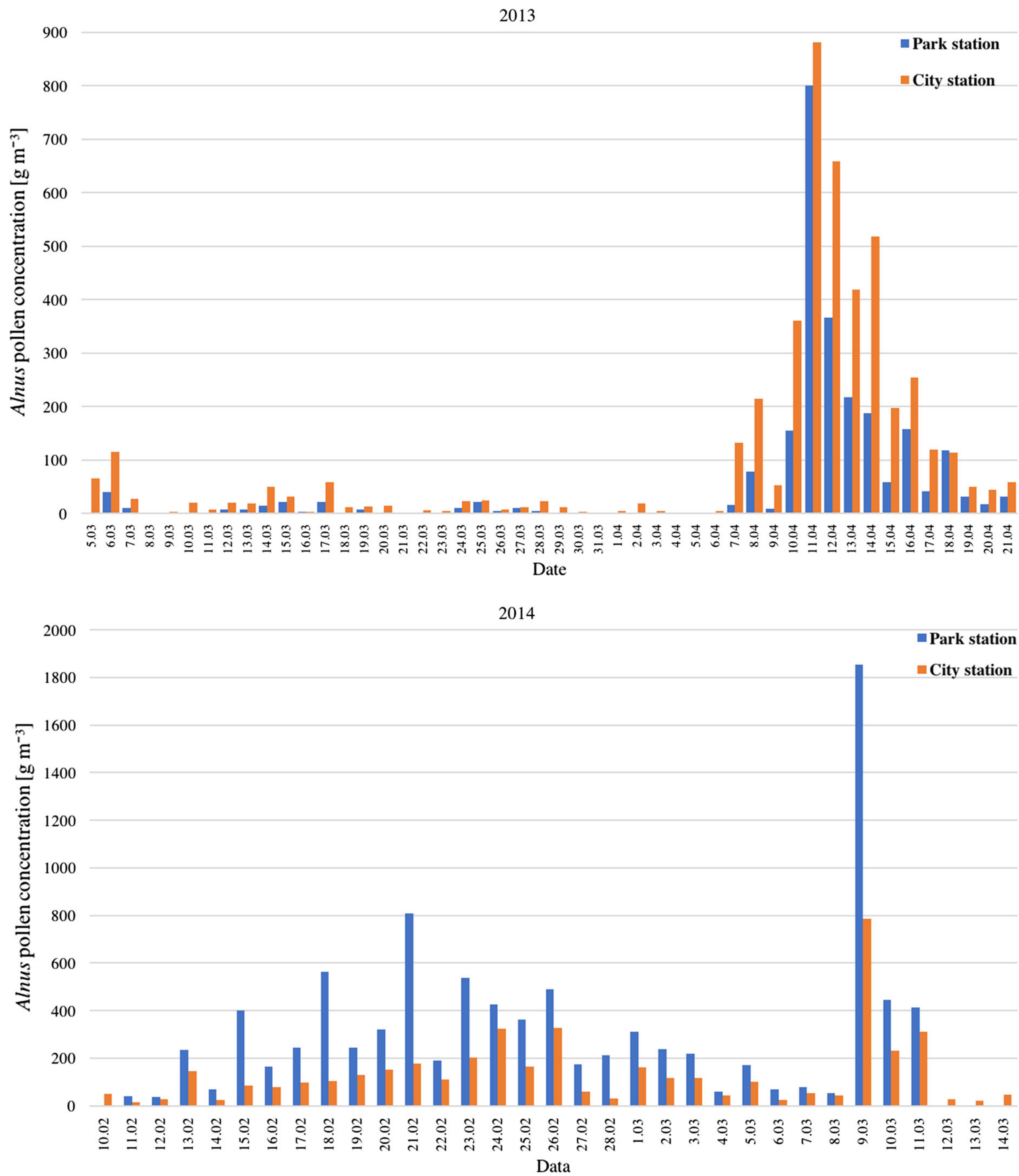

Fig. 5 Distribution of Alnus pollen in 2013 and 2014 for the Park station and the City station

trajectories' frequency for both City and Park stations was very low and did not exceed 0.04 (p value $< 2.2e{-}16$) and decreased with increasing height of trajectories.

During the whole *Alnus* pollen season in 2014, the inflow of air masses was mainly from the south and south-east. At 1500 m, the main inflow of air masses was from the west (Fig. 9). At both altitudes, the air

Table 5 Spearman's correlation coefficient for Alnus pollen and meteorological data from the same day

	Park station		City station	
	2013	2014	2013	2014
T	0.09	0.06	**0.33**	0.00
T_{max}	0.22	**0.74**	**0.44**	**0.41**
T_{min}	− 0.25	− **0.45**	− 0.07	− 0.25
RH	− **0.65**	− 0.17	− **0.54**	0.05
RH_{max}	− **0.38**	**0.38**	− 0.25	**0.35**
R_{sum}	− **0.56**	− 0.21	− **0.55**	− 0.29
R	− **0.40**	− 0.21	− **0.39**	− **0.34**
R_{max}	− **0.38**	− 0.20	− **0.37**	− 0.33
V	0.00	− 0.03	− 0.06	0.01
SD	**0.45**	**0.41**	**0.48**	**0.34**
SR_t	**0.60**	**0.58**	**0.61**	0.33
SR_d	**0.45**	− **0.43**	**0.33**	− 0.12

Bold—statistically significant

Table 6 Spearman's correlation coefficient for Alnus pollen and meteorological data from the previous day

	Park station		City station	
	2013	2014	2013	2014
T	0.08	− 0.12	0.17	− 0.22
T_{max}	0.16	**0.39**	0.21	0.22
T_{min}	− 0.14	− 0.12	− 0.04	− 0.18
RH	− **0.57**	0.01	− **0.44**	0.27
RH_{max}	− **0.45**	0.17	− **0.44**	0.32
R_{sum}	− **0.53**	− 0.25	− **0.46**	− 0.24
R	− **0.37**	− 0.14	− 0.30	− 0.17
R_{max}	− **0.33**	− 0.14	− 0.27	− 0.17
V	− 0.10	− 0.16	− 0.17	− 0.11
SD	**0.39**	0.33	**0.30**	**0.38**
SR_t	**0.47**	**0.40**	**0.38**	0.19
SR_d	0.14	− 0.08	− 0.01	0.07

Bold—statistically significant

masses inflow was over areas covered with *Alnus* trees. The correlation coefficient between the maps of trajectories' frequency for both City and Park stations did not exceed 0.38 (p value $< 2.2e{-}16$) and decreased with increasing height of trajectories.

During the "high" group in 2014 (days with *Alnus* pollen concentration above 85 pollen grains m^{-3}), at 50 m the inflow of air masses was mainly from the south-eastern direction, but the southern direction was also marked. At 1500 m, the significance of air masses from the south-east was lower, while the highest contribution of air masses was from the western direction (Fig. 10). At both altitudes, trajectories crossed the area at which *Alnus* trees are observed. The correlation coefficient between the maps of trajectories' frequency for both City and Park stations differed according to different altitudes of trajectories and reached 0.44 for 50 m and 0.34 for 1500 m (p value 2.2e−16).

Major differences between the stations and arriving air masses were found for the "peak" group in 2014 (days for which the measured pollen concentrations increased rapidly in comparison with the previous day). At 50 m, the main direction of inflow was from the south and south-east for the City station and south with little contribution from the south-east for the Park station. At 1500 m, for the City station, the inflow of air masses was scattered from the north-eastern, eastern, south-eastern, southern, and south-western directions. For the Park station, air masses came mainly from the south-western direction (Fig. 11). At both altitudes, trajectories crossed the area at which *Alnus* trees are present. The correlation coefficient between the raster of trajectories' frequency was small and did not exceed 0.17 (p value $< 2.2e{-}16$) and decreased with increasing height of trajectories.

4 Discussion

According to Kasprzyk (2010), the start of pollination can vary even on a local scale, depending on the type of habitat. Her analysis has shown that even a small increase in temperature or more sunlight favours pollination and an earlier start to the season of *Corylus* (Kasprzyk 2010). Pollen grain concentration is sensitive to temperature, which was confirmed by Dąbrowska-Zapart et al. (2018) for *Alnus* and by Gottardini and Cristofolini (1997) for *Corylus*. In our study, we observed the negative significant correlation between *Corylus* pollen concentrations and daily minimum temperature. High pressure, low cloudiness, and calm wind speed during the night are favourable for low minimum temperatures. On contrary, the same

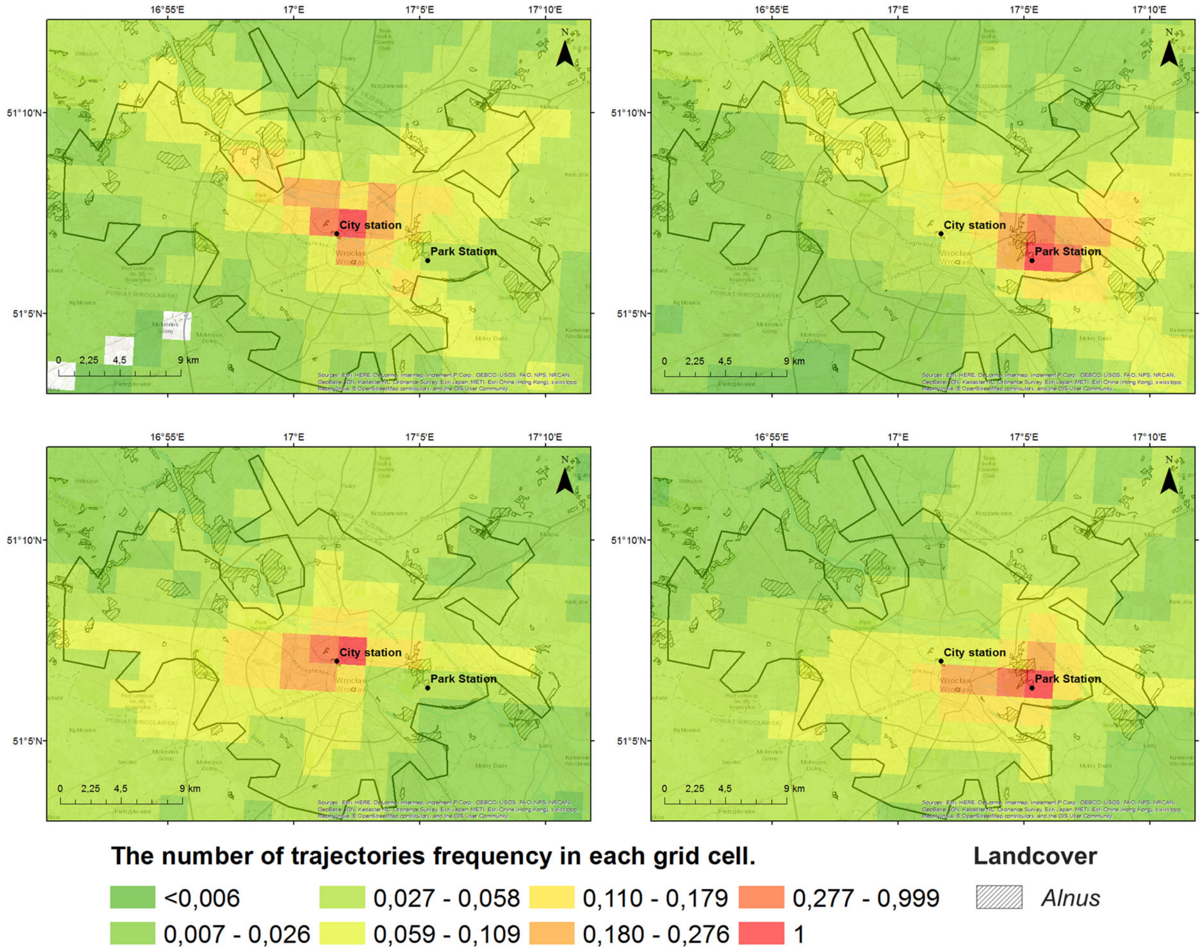

Fig. 6 Trajectories' frequency in each grid cell for the Alnus season in 2013 for the City station (left side) and the Park station (right side) for 50 m and 1500 m agl. (From top to bottom row)

weather patterns are favourable to increased solar radiation and relatively high temperatures during the day (Szewczak 2014). During days with high solar radiation (and increased daytime temperatures), some *Corylus* shrubs could release their pollen earlier. For the same day were observed relatively low minimum air temperatures. Puc and Kasprzyk (2013) also claimed that differences in the time and fluctuation of the pollen season are caused by local weather conditions. Piotrowska-Weryszko (2013) showed that local meteorological factors influence the pollen peak shift (in 2002, it reached over a month) between stations located in different regions of Poland. Our study has also shown that the meteorological conditions have an impact on the variability of pollen season. This is proven by the statistically significant correlation between meteorological factors and pollen concentration from the same day.

As was shown in other studies, meteorology from a longer period (e.g. sum of the temperatures several weeks before the start of the pollen season) is important to start flowering. Especially at the start of the season, air temperature preceding *Alnus* or *Corylus* pollination is very important, because it influences on the pollen emission (Rodriguez-Rajo et al. 2004; Dąbrowska-Zapart 2008; Piotrowska and Kaszewski

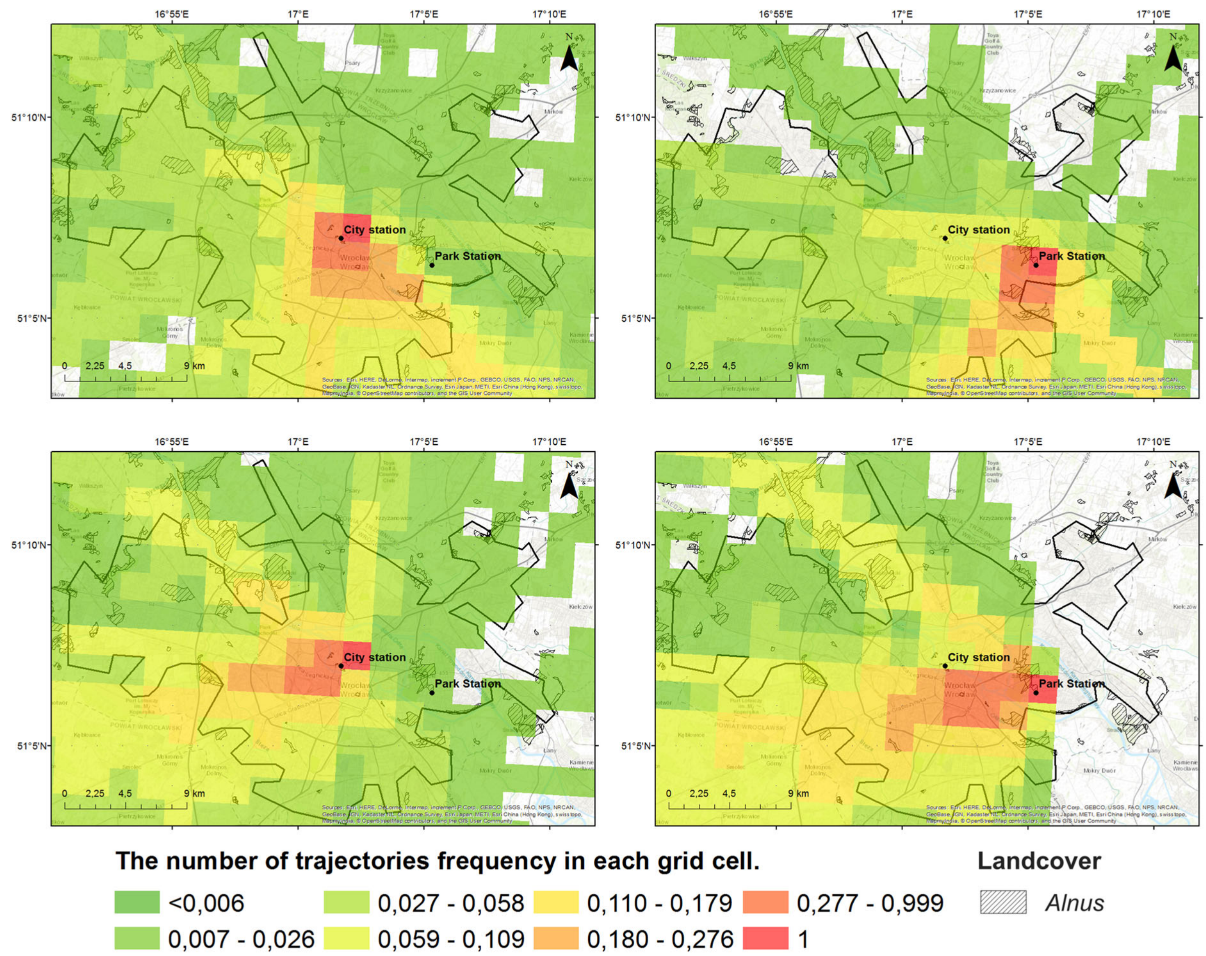

Fig. 7 Trajectories' frequency in each grid cell for the Alnus "high" group in 2013 for the City station (left side) and the Park station (right side) for 50 m and 1500 m agl. (From top to bottom row)

2009; Myszkowska et al. 2010; Malkiewicz et al. 2016). In our study, we have shown that meteorological parameters from the same day as pollen concentration have a greater influence on pollen concentration than meteorological parameters from the previous day. Similar dependences showed also Kasprzyk (2013)—in her findings, the correlation coefficient between *Corylus* and *Alnus* pollen grains and current meteorology conditions was higher than for meteorology condition from the previous day.

Analysis of trajectories is widely used in order to identify the most probable location of air pollution sources (Cesari et al. 2014; Godłowska et al. 2015) as well as any pollen source location or movement (Smith et al. 2005; Stach et al. 2007; Bilińska et al. 2017). The back-trajectories were used in a study conducted by Skjøth et al. (2015) which investigated the source of *Betula* pollen in Wrocław and Worcester. Their study showed that the pollen concentration in the air is mainly provided by local trees (Skjøth et al. 2015). According to Myszkowska et al. (2010), *Alnus* is sensitive to wind speed, which promotes the release and distribution of its pollen. In the case of *Corylus*, Stępalska et al. (2016) showed that its pollen remains in the air longer than flowering season lasting, and thus, a long-range transport and analysis of trajectories may play an important role in understanding *Corylus* pollen air concentrations.

In our study, back-trajectories have shown that the inflow of air masses was the most diverse between the

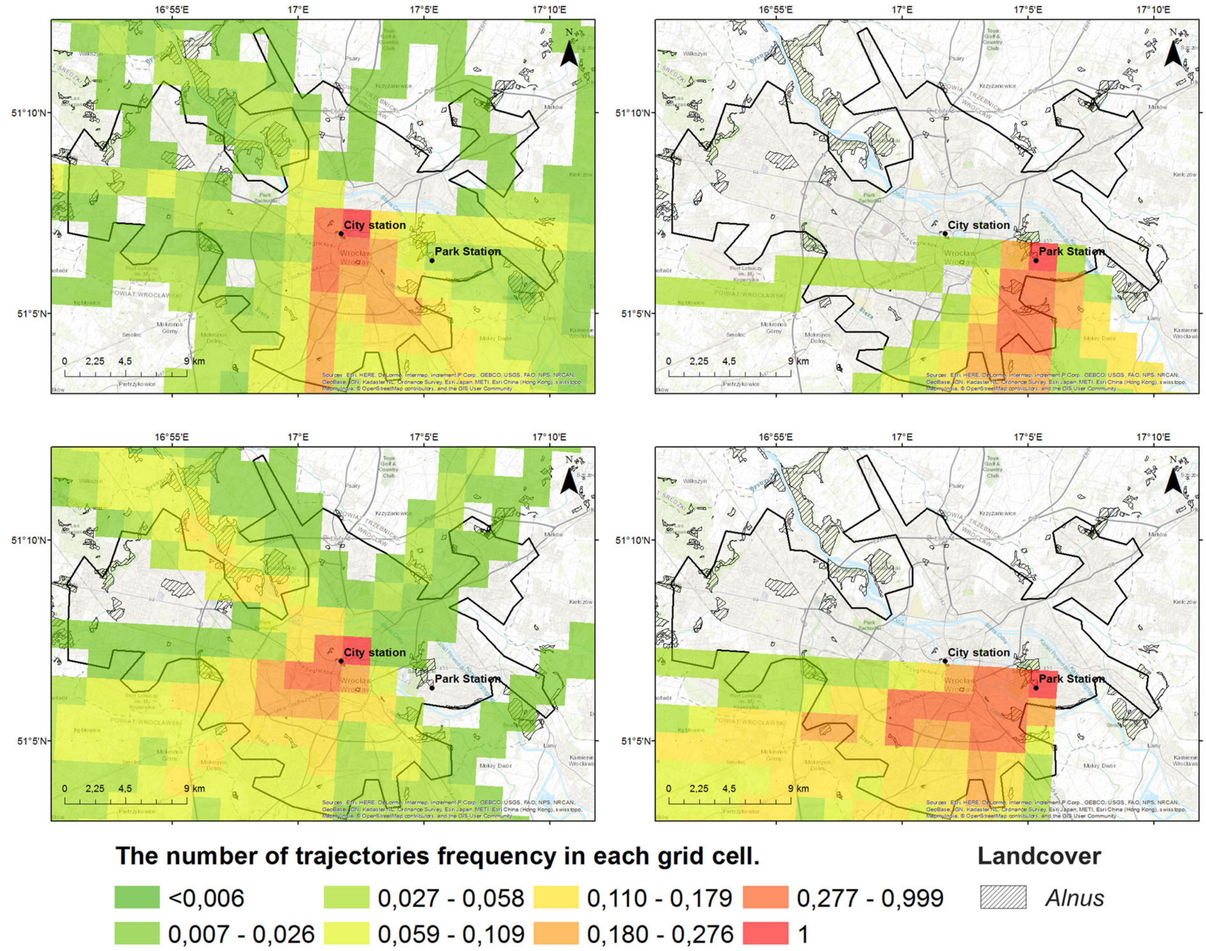

Fig. 8 Trajectories' frequency in each grid cell for the Alnus "peak" group in 2013 for the City station (left side) and the Park station (right side) for 50 m and 1500 m agl. (From top to bottom row)

stations for the *Alnus* high-concentration episodes, especially in 2014. In other cases (trajectories for the whole season of *Corylus* and *Alnus* both in 2013 and 2014 and high *Alnus* episodes in 2013), the transport of air masses was also strongly different for both stations. It suggests that in explaining the variability of the pollen season between two stations located close to each other, both the meteorological conditions and surrounding of the sampling sites are important, which was also noted by Charalampopoulos et al. (2018). According to Rojo et al. (2015), green areas in close proximity to pollen traps strongly influence the number of pollen in the air. Borycka and Kasprzyk (2018) found that the *Alnus* SPIn and daily concentration in Rzeszów (Poland) were higher in the suburbs, where more alder trees grow, than in downtown. In our study, the start of the pollen season in the case of *Corylus* was observed earlier at the Park station than at the City station in each of the analysed year. This shift between the start of the pollen season reached even 25 days in 2013. The earlier appearance of *Corylus* pollen at the Park station can be caused by the fact that in close proximity to the Park station there are a few *Corylus* shrubs and a bit further there is a big park with higher number of hazel. There is no hazel shrub in the vicinity of the City station. In the case of *Alnus*, these differences were not as pronounced as in the case of *Corylus*, in terms of both start/end of the pollen season and observed maximum concentrations of pollen. This might be explained by the fact that

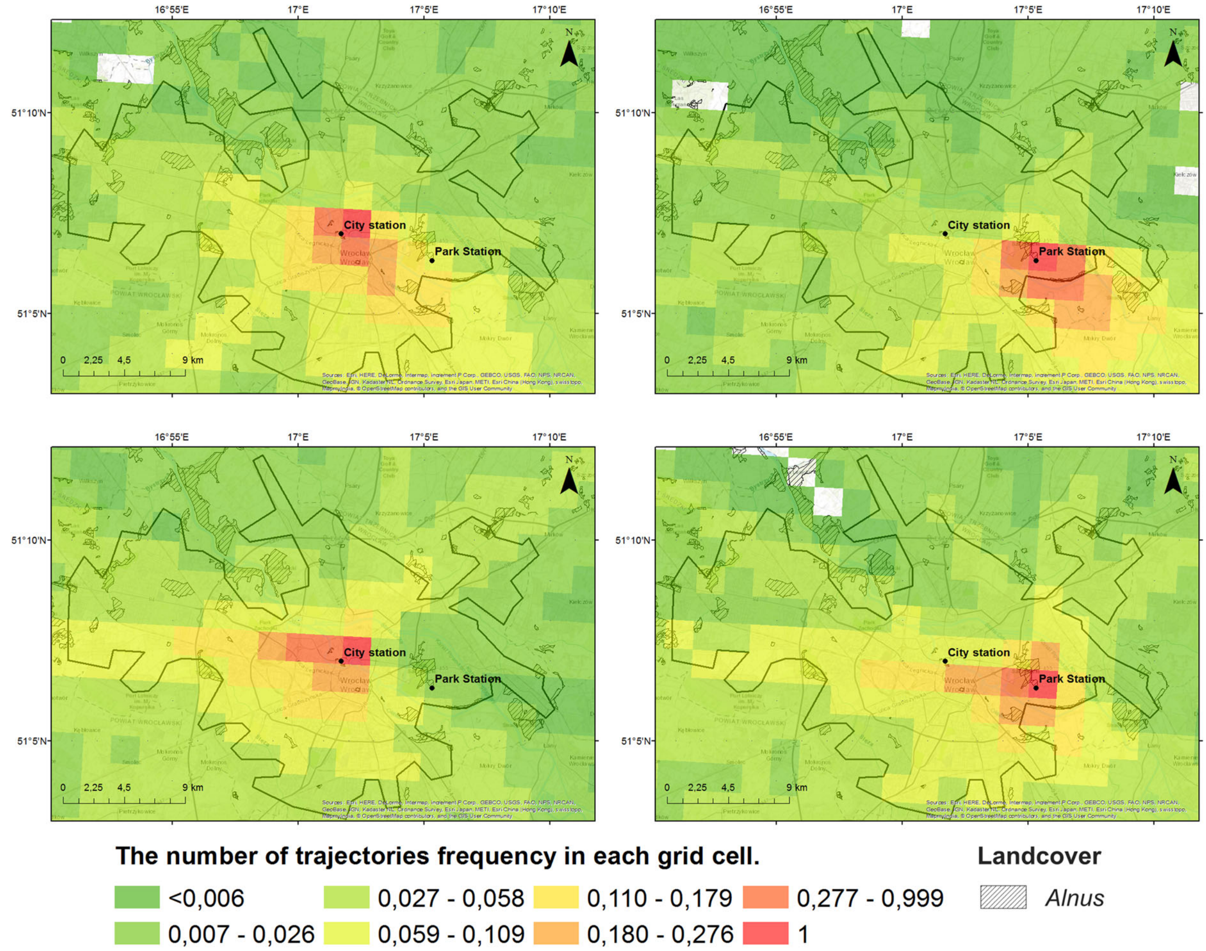

Fig. 9 Trajectories' frequency in each grid cell for the Alnus season in 2014 for the City station (left side) and the Park station (right side) for 50 m and 1500 m agl. (From top to bottom row)

Alnus trees grow in a short distance from both stations. The next evidence of the significance of the vicinity of station on the pollen concentration is the SPIn of *Alnus* at Park station in 2013 and 2014. In 2013, the *Alnus* SPIn was almost twice lower than in 2014. This could be linked to the land-use changes that were related to the development of the river system in Wrocław. In 2012–2013, embankment of Odra River near the Park station was rebuilt, whereas the areas close to the rivers in Wrocław are the main areas where the *Alnus* trees grow. During this redevelopment, some trees were removed and this could be the reason why lower SPIn was observed in 2013. However, we are not able to support this information quantitatively.

Also, analysis of trajectories on different heights suggests that the main source of pollen is local trees rather than distant transport. At 1500 meters, the dominant flow showed by trajectories was from western directions which is consistent with the general climatological circulation for Poland (Woś 1999). More important are trajectories calculated at height of 50 m above ground level. Their direction can show the possible sources of pollen. In our study, maps with trajectories' frequency at 50 m above ground level

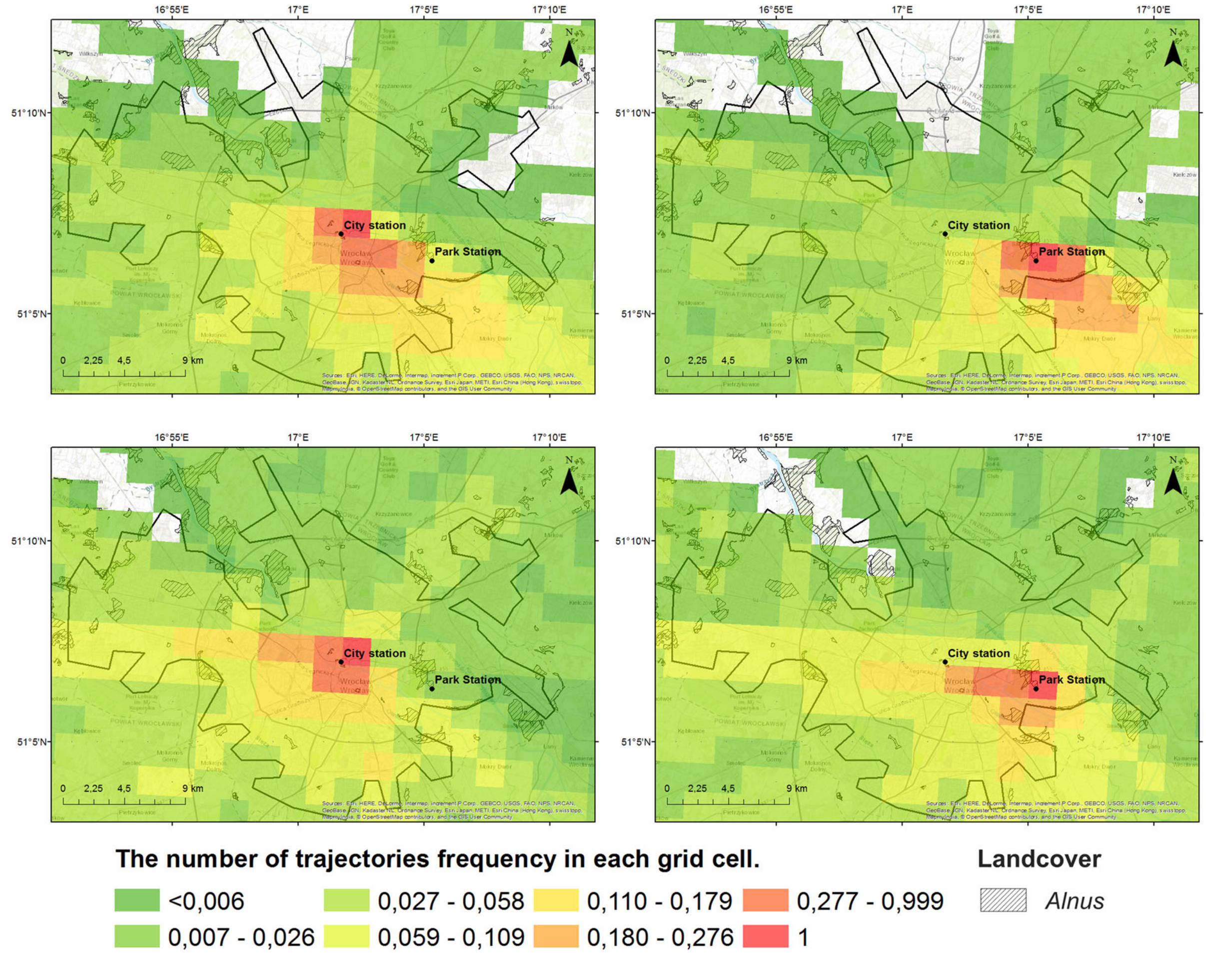

Fig. 10 Trajectories' frequency in each grid cell for the Alnus "high" group in 2014 for the City station (left side) and the Park station (right side) for 50 m and 1500 m agl. (From top to bottom row)

show that in the case of "high" or "peak" groups, air masses flow above the area with *Alnus* trees and *Corylus* shrubs.

Our analyses of trajectories have shown that there are the differences in the inflow of air masses even for two stations located close to each other. The correlation coefficient between the maps of trajectories' frequency did not exceed 0.44 and decreased with increasing height of trajectories, which also confirmed the differences in inflow between the two stations. It is particularly visible in the case of *Alnus* episode, where at higher altitudes the direction of inflow of air masses inflow is significantly different, which is also confirmed by the low or insignificant correlation coefficient.

5 Conclusion

Our study has shown that it is possible that the pollen concentration varies greatly even in sampling sites located close to each other (c.a. 4 km). This variability can differ according to years. The most important parameter that causes differences between stations is the presence of *Alnus* trees or *Corylus* shrubs in close proximity. Meteorological factors contribute to the

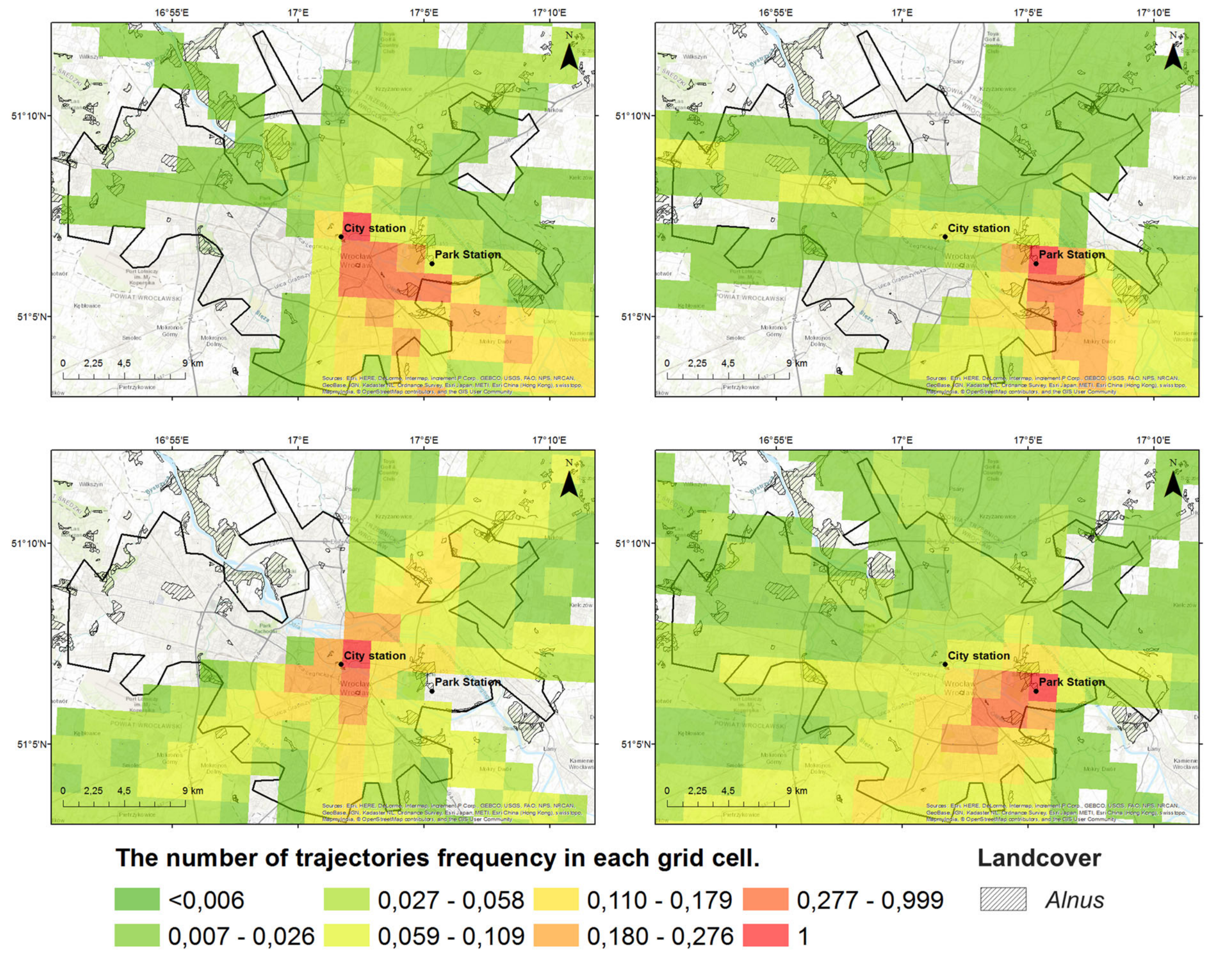

Fig. 11 Trajectories' frequency in each grid cell for the Alnus "peak" group in 2014 for the City station (left side) and the Park station (right side) for 50 m and 1500 m agl. (From top to bottom row)

variability of the pollen season. Higher correlation coefficients are more commonly found between pollen concentrations and meteorological factors observed in the same day than with meteorology from the previous day. The analysis of meteorological conditions and influence of air transport on pollen concentration, spatial distribution of tree species, and impact of air transport on pollen concentration has provided the reasons for the difference in pollen levels at two stations.

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