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Citation style: Dąbrowska-Zapart Katarzyna, Niedźwiedź Tadeusz. (2020). The impact of weather conditions on hazel pollen concentration in Sosnowiec (Poland) in 1997-2019. "Aerobiologia" (2020), doi 10.1007/s10453-020-09661-9

Aerobiologia
https://doi.org/10.1007/s10453-020-09661-9

ORIGINAL PAPER

The impact of weather conditions on hazel pollen concentration in Sosnowiec (Poland) in 1997–2019

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Received: 26 November 2019 / Accepted: 12 September 2020

Abstract The goal of this study was to compare hazel pollen seasons in Sosnowiec in 1997–2019 and to analyse the impact of weather conditions on these seasons. The measurements were conducted using a volumetric method with a Burkard spore trap. The duration of pollen seasons was determined using the 98% method. SPI (Seasonal Pollen Index) was calculated as the sum of daily pollen concentrations in a given season. The measurements showed that high temperatures in January and February had an impact on the beginning of the hazel pollen season. They revealed that there are positive correlations with temperatures and sunshine hours long before the season, i.e. 210–180 days before. The daily hazel pollen concentration in Sosnowiec showed a positive and statistically significant correlation with air temperature, sunshine hours, and average and maximum wind speed. Negative correlation was demonstrated for snow cover depth and relative humidity of the air. Daily concentration levels depend also on the type of weather front as well as direction of air mass flow and its type. Variance analysis showed that the highest concentrations of hazel pollen grains were recorded when warm air moves from the south and south–western direction, whereas the lowest ones were noted for air moving from the east, south–east, north and north–east directions. Atmospheric precipitation, snow cover depth, and average, maximum, minimum and near-the-ground temperatures in the season also had an impact on the SPI of hazel pollen grains. High positive correlation coefficients were also observed in the case of thermal conditions, sunshine hours, relative humidity and precipitation from July to September in the year preceding a given pollen season. The duration of the hazel pollen season depends on precipitation, snow cover depth and temperature during a given season.

Keywords Hazel pollen · *Corylus* · Weather types · Weather conditions · Statistical analysis

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1 Introduction

Hazel pollen allergens along with grass, birch and alder are the most common cause of allergic rhinitis and conjunctivitis in Central and Northern Europe (Wihl et al. 1998). They appear very early over Poland, i.e. at the end of January, in February or March. Common hazel (*Corylus avellana*) is the only native hazel species in Poland. It is very common in the entire country, growing in forests, clear-cuts and glades. In the mountains, it grows even in lower subalpine forests (Seneta and Dolatowski 2004).

Published online: 07 October 2020

Numerous ornamental varieties are often planted in gardens and parks. The moment when hazel blossoms appear is considered as the beginning of botanical early spring. The onset and peak of hazel pollen production is highly variable. Hazel blossoming onset depends on weather conditions and differs year by year (Kalinovych et al. 2016). The total number of pollen grains produced by the plant and intensity of pollen shedding depend on weather conditions present during a given pollen season or directly before it (Kasprzyk et al. 2004; Emberlin et al. 2007). Weather conditions occurring when thecae are formed, i.e. in the late summer of the previous year, are also of great importance (Emberlin et al. 2007; Kim et al. 2011; Piotrowska-Weryszko 2013). Threshold hazel pollen concentration, i.e. a concentration associated with the onset of symptoms in hypersensitive individuals, amounts to 35 grains/m^3 of air in Poland (Rapiejko et al. 2007). If the concentration reaches 80 grains/1 m^3 of air, pollinosis is observed in all individuals allergic to hazel pollen. Although hazel pollen is not as highly concentrated in the air, it plays a great role in allergology. It cross-reacts with birch and alder pollen and with some vegetables and fruits. Individuals allergic to hazel pollen may also present allergic symptoms when birch and alder are shedding pollen as well as after ingestion of e.g. an apple or a celery (Rapiejko and Lipiec 2007). Long-term studies on the dynamics of pollen seasons conducted in Poland (Sosnowiec) revealed a large variability of hazel seasons.

Sosnowiec is located in the south of Poland, in the eastern part of the Silesian Upland (Fig. 1). Despite a substantial density of residential and industrial buildings, the city is a habitat of numerous species of vascular plants (Tracheophytes) that belong to many botanical families. According to Jędrzejko (1993), green areas account for approx. 24.7% of the city area.

Climate conditions of the Silesia Upland are largely variable and irregular. The city is located in a temperate climate zone, transitional between a marine and a continental one. For most days throughout the year (65%), the weather is formed under the influence of polar sea air moving from the Atlantic Ocean. The average annual temperature is 9.2 °C, with July being the warmest month (19.5 °C), and January the coldest month (− 1.2 °C). The average annual rainfall amounts to 735 mm. Snowfall is noted on approx. 50 days a year. The average number of days with snow cover is 66, while the average snow cover depth is 25 cm. High weather variability and rainfall accompany weather fronts moving over Sosnowiec during 40.5% of the days a year. As far as wind in Sosnowiec is concerned, a west wind is the most prevailing one, followed by southern, north-west and south-west winds. The average wind speed in Sosnowiec is estimated at approx. 3.1 m/s (Niedźwiedź and Małarzewski 2016).

Fig. 1 The geographic location of Sosnowiec in Central Europe ▶ (www.vecteezy.com/map-vector)

The aim of this study was to compare the concentrations of hazel pollen grains measured over 23 years and to analyse the impact of weather elements on selected properties of its pollen season in Sosnowiec, i.e. beginning and end of the pollen seasons, maximum daily concentration, days with maximum concentration, duration of the pollen season and annual pollen count (SPI—Seasonal Pollen Index).

2 Materials and methods

Concentrations of hazel pollen grains were analysed based on data obtained in Sosnowiec in 1997–2017. Aerobiological measurements were performed using a volumetric method with a Burkard spore trap placed at the building of the Faculty of Natural Sciences University of Silesia in Katowice, in the northern part of the Sosnowiec district Pogoń where there is low-density apartment-type housing. The trap is positioned approx. 20 m above the ground on the laboratory building roof. The geographical coordinates of the measurement point are as follows: 50° 17′ 50″N and 19° 08′ 20″E. A meteorological station of the Department of Climatology, which was the source of weather data, is located nearby at the altitude of 263 m above sea level. Weather data were collected from a Faculty meteorological station, which is located nearby at the altitude of 263 m above sea level. Additional data came from the synoptic weather station of the Institute of Meteorology and Water Management in Katowice, which is located approx. 10 km southwest of Sosnowiec. In the study, we used the average daily and monthly values of weather elements, such as: average, near-the-ground, maximum and minimum air temperature, sunshine hours, relative humidity, average and


Europe
www.vecteezy.com/map-vector
BALTIC SEA
RUSSIA
LITHUANIA
BELORUSSIA
GERMANY
CZECH REPUBLIK
SLOVAKIA
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100 km
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22°
24°
54°
52°
50°
16°
18°

maximum wind speed, precipitation, snow cover occurrence and depth, direction and type of atmospheric circulation (Niedźwiedź 1981, 2004, 2006).

Obtained material were stained with alkaline fuchsine on the surface of 4 horizontal strips (Mandrioli et al. 1998), mounted on a glass slide and observed using a transmitted light microscope Nikon Eclipse H550S. The duration of pollen seasons was determined using the 98% method. It was assumed that they began and ended on days with 1% and 98% of annual pollen count, respectively (Emberlin et al. 1994; Spieksma and Nikkels 1998).

The following properties of the season have been defined: date of its beginning and end, duration, SPI, maximum daily concentration, date of the highest concentration and number of days on which the concentration exceeded the threshold values (35–80 grains/m^3). Threshold values were based on hazel pollen air concentration, which is reported to cause allergic symptoms in Poland (Rapiejko et al. 2007). Dates related to the beginning, end and peak of pollen seasons were converted into the day of the year, counting from the 1st of January.

The following descriptive statistics were used to analyse differences in the course of pollen seasons in the years studied: arithmetic mean, minimum and maximum pollen count, standard deviation and coefficient of variation. Variation for each property of a given pollen season was evaluated using linear regression. In order to analyse individual variables by means of basic descriptive statistics, dates on which the given property of pollen seasons was noted were replaced with the number of days since the beginning of the year. The following interpretation was applied to assess the coefficient of variation (V): $V < 20\%$—low variation, $20\% < V < 40\%$—average variation, $40\% < V < 100\%$—high variation.

A parametric analysis (Pearson's correlation coefficient) or a nonparametric analysis (Spearman's rank correlation coefficient) was conducted to determine the impact of weather conditions on examined properties of hazel pollen seasons, depending on the distribution of data (verified using the Shapiro–Wilk test with a level of 0.05; the result has not been presented). Analysis of variance was conducted along with multiple-comparison post hoc LSD tests, and a backward linear regression model was developed. Power of correlation was assessed with the following ranges: 0–0.3 poor correlation, 0.3–0.5 moderate correlation, 0.5–0.7 strong correlation, 0.7–1 very strong correlation.

3 Results

Significant differences in analysed properties of hazel pollen seasons were observed throughout the period of 23 years (Table 1). The beginning of the season and maximum daily concentration proved to be the most variable properties of hazel pollen seasons, as evidenced by a high coefficient of variation (Table 2). A relatively low coefficient of variation was determined for the date of the end of the pollen season, the maximum concentration date and annual pollen count (SPI—Seasonal Pollen Index) (Table 2).

An extremely low SPI of hazel pollen was observed in 1998 (329 grains) and in 2012 (334 grains). In contrast, the highest SPI in the examined period of time was observed in 2001 (875 grains) and in 2004 (833 grains) (Table 1). Analysis of the SPI of hazel pollen in Sosnowiec did not reveal any cyclicity in the occurrence of years with high SPI alternating with years with low SPI. Years with lower SPI interchanging with years with high SPI were noted in the analysed period, but they did not show any regularity (Fig. 2). No significant trends were observed in the analysed characteristics of the pollen season in the 23-year study period. However, a minor but statistically insignificant decrease in SPI was noted (Fig. 2).

The highest daily concentration of 304 grains/m^3 was observed in 1999. It was the record-breaking concentration in the study period. The season on average began in the first decade of February. Hazel pollen in the air in Sosnowiec was noted at the earliest in 2007, i.e. on the 10th of January, and at the latest in 2005, i.e. on the 14th of March, which is over two months later. Pollen seasons lasted on average for 54 days. The longest and the shortest seasons were found in 2018 (82 days) and in 2005 (25 days), respectively (Table 1). Variation of this property (27.7%) can be classified as average, as it falls in the range of $20\% < V < 40\%$ (Table 2).

The greatest number of days with threshold concentrations, at which individuals allergic to hazel pollen present with allergic symptoms, was noted in 2001, 2002, 2004 and 2005 (Table 1).

Weather elements are, apart from the pollen-shedding rhythm of individual plants, important

Table 1 Characteristics of hazel pollen seasons in Sosnowiec

Year	Beginning of the pollen season	End of the pollen season	Duration of the pollen season	Maximum concentration	Date of max concentration	Annual total (SPI)	≥ 35 grains/m^3	≥ 80 grains/m^3
1997	19.02 (50)	6.04 (96)	46	75	24.02 (55)	463	6	0
1998	24.01 (24)	21.03 (80)	56	70	21.02 (52)	329	2	0
1999	8.02 (39)	27.03 (86)	47	304	3.03 (62)	667	3	2
2000	3.02 (34)	3.04 (94)	60	91	29.02 (60)	466	5	1
2001	7.02 (38)	31.03 (90)	52	99	12.03 (71)	875	8	2
2002	2.02 (33)	19.03 (78)	45	86	12.02 (43)	680	7	1
2003	8.03 (67)	3.05 (123)	56	106	26.03 (85)	606	5	2
2004	3.02 (34)	3.04 (94)	60	191	18.03 (78)	833	6	4
2005	14.03 (73)	8.04 (98)	25	135	25.03 (84)	597	7	2
2006	19.02 (50)	27.04 (117)	67	214	30.03 (89)	770	4	3
2007	10.01 (10)	27.03 (86)	76	73	6.03 (65)	614	3	0
2008	21.01 (21)	25.03 (85)	64	74	23.02 (54)	688	6	0
2009	28.02 (59)	17.04 (107)	48	45	10.03 (69)	454	3	0
2010	25.02 (56)	11.04 (101)	45	138	20.03 (79)	655	6	2
2011	9.02 (40)	1.05 (121)	81	106	14.03 (73)	577	5	3
2012	3.03 (63)	10.04 (101)	38	90	16.03 (76)	334	4	1
2013	24.02 (55)	22.04 (112)	57	87	6.03 (65)	561	3	1
2014	17.01 (17)	23.03 (82)	65	54	17.02 (48)	671	6	0
2015	15.02 (46)	1.04 (91)	45	100	18.03 (67)	573	4	2
2016	29.01 (29)	5.04 (96)	67	94	9.02 (40)	576	4	1
2017	22.02 (53)	25.03 (84)	31	77	3.03 (62)	440	6	0
2018	18.01 (18)	10.04 (100)	82	36	4.04 (94)	551	1	0
2019	10.02 (41)	18.03 (77)	36	100	26.02 (57)	500	4	1

The numbers in parentheses indicate the consecutive day from the beginning of the pollen season

factors that have an impact on pollen concentration in the air. They also determine the occurrence of hazel pollen in the air. Statistical analyses revealed the impact of weather conditions on seasonal and daily variability of hazel pollen grains. Air temperature, which highly fluctuates in hazel pollen season, seems to play the most crucial role.

Precise prediction of the beginning of a hazel pollen season is hard to achieve. We observed that the beginning dates differ significantly in analyzed years. Correlation coefficients calculated between the average of selected weather elements from the period of 5–210 days preceding the season and the beginning date of the pollen season show that conditions immediately preceding the season date, and those that occur long before the beginning of it affect the date on which pollen grains appear in the air (Table 3). Undoubtedly, temperature has the greatest impact on the beginning of the hazel pollen season. Low temperatures delay the appearance of this taxon's pollen in the air. It is worth emphasizing that the highest correlation coefficients were obtained for average values from 180 and 210 days before the beginning of the pollen season. This implies that temperatures in the period starting from the previous summer (June–August) to the pollen-shedding day play the most crucial role. The higher the average temperature during this period, the earlier hazel starts shedding pollen. The impact of the near-the-ground temperature from the period immediately preceding the season (from 5 days in particular) is also significant. From all observed weather elements, relative humidity and sunshine hours have the lowest impact

Table 2 Statistics of hazel pollen season in Sosnowiec

	Beginning of the season (days)	End of the season (days)	Duration of the season (days)	Maximum daily concentration (grains/ m^3)	Maximum daily concentration date	Annual total (SPI)
Data from the years 1997–2019						
$\bar{x}$	41	96	54	106	66	586
Min	10 (2007)	77 (2019)	25 (2005)	36 (2018)	40 (2016)	329 (1998)
Max	73 (2005)	123 (2003)	82 (2018)	304 (1999)	94 (2018)	875 (2001)
SD	17.0	13.3	15.1	59.5	14.5	139.0
V (%)	41.1	13.9	27.7	56.0	21.8	23.7

$\bar{x}$ arithmetic mean. Min—minimal concentration of pollen grains. Max—maximum concentration of pollen grains. SD—standard deviation. *V*—coefficient of variation

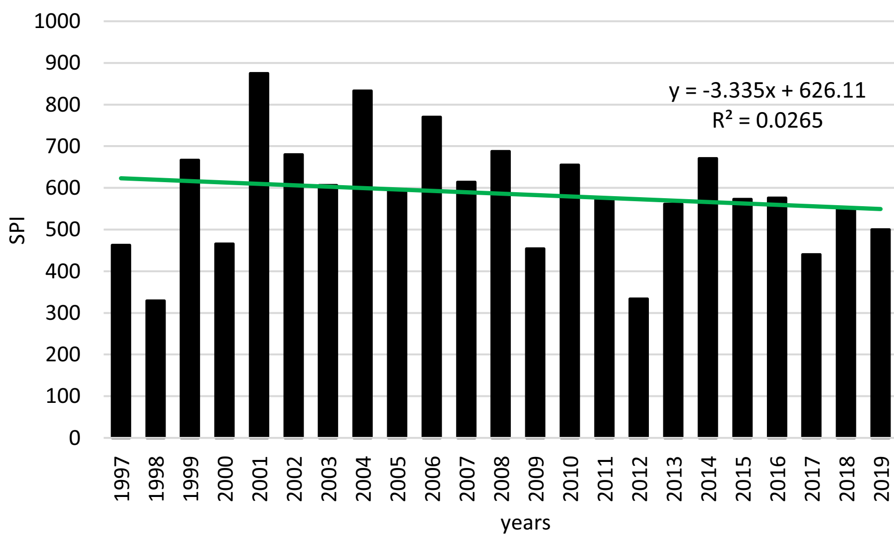

Fig. 2 The seasonal pollen index (SPI) of hazel

on the hazel pollen season. No significant correlations were found also for precipitation (Table 3).

Temperatures in January and February turned out to be the most important among the average monthly values of the weather conditions that have an impact on the beginning of the hazel pollen season (Table 4). High positive correlation coefficients mean that high temperatures in January and February speed up the appearance of hazel pollen in the air. Extremely high correlation coefficients were demonstrated for temperature from the period of January–February.

The results of Spearman's correlation between the daily count of hazel pollen grains and individual constituents determining the weather conditions are presented in Table 5.

A series of analyses of Spearman's rank correlation coefficient revealed that daily hazel pollen count had a statistically significant relationship with maximum temperature $r = 0.39$; $p < 0.001$, minimum temperature $r = 0.20$; $p < 0.001$, near-the-ground temperature $r = 0.22$; $p < 0.001$ and average temperature $r = 0.37$; $p < 0.001$. These correlations were positive, which means that measured hazel pollen count

Table 3 Pearson's coefficient values determining the dependency between the beginning of the pollen season and the weather conditions in the preceding period in a range from 5 to 210 days

Number of days preceding the season	Weather elements						
	Average *T*	Minimum *T*	Maximum *T*	*T* 5 cm (near-the-ground)	Precipitation	Relative humidity	Sunshine duration
5	− 0.68*	− 0.76**	− 0.52	− 0.80***	0.01	− 0.44	0.55
10	− 0.57	− 0.65*	− 0.46	− 0.58	− 0.16	− 0.28	0.50
15	− 0.61*	− 0.74**	− 0.42	− 0.69*	− 0.28	− 0.59	0.51
20	− 0.74**	− 0.84***	− 0.57	− 0.81***	− 0.37	− 0.50	0.56
25	− 0.79**	− 0.84***	− 0.67*	− 0.83***	− 0.50	− 0.68*	0.60
30	− 0.71**	− 0.74**	− 0.64*	− 0.75**	− 0.22	− 0.66*	0.53
40	− 0.78**	− 0.81***	− 0.73**	− 0.82***	− 0.33	− 0.62	0.58
60	− 0.77**	− 0.78**	− 0.76**	− 0.79**	0.10	− 0.61	0.40
90	− 0.80***	− 0.80***	− 0.78**	− 0.81***	− 0.07	− 0.48	0.09
120	− 0.90***	− 0.86***	− 0.85***	− 0.86***	− 0.06	− 0.33	− 0.46
150	− 0.89***	− 0.89***	− 0.90***	− 0.88***	− 0.37	− c0.19	− 0.60
180	− 0.93***	− 0.92***	− 0.93***	− 0.91***	− 0.51	0.21	− 0.77**
210	− 0.94***	− 0.94***	− 0.93***	− 0.93***	− 0.61	0.09	− 0.77**

$p < 0.05$*; $p < 0.01$**; $p < 0.001$***

Table 4 Pearson's coefficients between the average monthly values of the weather conditions and the hazel pollen season beginning date

Meteorological conditions	Beginning of the pollen season
Average January temperature	− 0.62*
Minimum temperature January	− 0.61*
Maximum temperature January	− 0.64*
Near-the-ground temperature January	− 0.67*
Average temperature February	− 0.70**
Minimum temperature February	− 0.82***
Maximum temperature February	− 0.76**
Near-the-ground temperature February	− 0.80***
Average temperature January–February	− 0.83***
Minimum temperature January–February	− 0.88***
Maximum temperature January–February	− 0.87***
Ground temperature January–February	− 0.86***

$p < 0.05$*; $p < 0.01$**; $p < 0.001$***

increased along with growing temperatures during the pollen season. The most powerful correlation was observed in the case of maximum temperature.

It was also demonstrated that daily hazel pollen count showed a statistically significant correlation with sunshine hours $r = 0.18$; $p < 0.01$, average wind speed $r = 0.21$; $p < 0.01$ and maximum wind speed $r = 0.19$; $p < 0.01$. Daily hazel pollen count was growing as sunshine hours and wind speed increased, but these correlations were not powerful.

It was also shown that daily hazel pollen count was related to relative humidity $r = -0.24$; $p < 0.01$ and snow cover depth $r = -0.30$; $p < 0.01$. These correlations were negative, which means that daily hazel pollen count decreased if humidity and snow cover depth were greater.

However, no statistically significant correlation was found between daily hazel pollen count and precipitation.

Table 5 The results of Spearman's correlation between the daily concentration of hazel pollen count and weather conditions

Weather conditions	Daily hazel pollen count
Maximum temperature	0.39***
Minimum temperature	0.20***
Near-the-ground temperature	0.22***
Average temperature	0.37***
Sunshine duration	0.18**
Average wind speed	0.21**
Maximum wind speed	0.19**
Relative humidity	− 0.24**
Precipitation	− 0.02
Snow cover thickness	− 0.30**

$p < 0.05$*; $p < 0.01$**; $p < 0.001$***

Afterwards, it was analysed whether and how daily hazel pollen count was affected by air circulation, i.e. the weather front, direction of air mass flow and its type. A series of one-way analysis of variance (one-way ANOVA) was performed to compare average results by the grouping factor. Intergroup comparisons were conducted by means of post-hoc LSD tests. Table 6 shows descriptive statistics for daily hazel pollen count by front type and result of the analysis of variance.

A one-way analysis of variance revealed that there was no statistically significant correlation between daily hazel pollen count and weather front type $p = 0.065$ (the result was at the limit of statistical significance). Figure 3 shows that the highest hazel pollen count was noted during a warm front (Fig. 3).

A one-way analysis of variance revealed that there was a statistically significant correlation between daily hazel pollen count and flow direction $p < 0.001$ (Table 7). Multiple comparisons showed that the highest average hazel pollen count was noted when warm air masses were moving from S + SWa (anti-cyclonic situation from the south and south west) direction ($M = 20.52$; SD = 27.09) or from S + SWc (cyclonic situation from the south and south-west) direction ($M = 19.49$; SD = 35.86) and the lowest one was recorded when air masses were moving from E + SEa (anticyclonic situation from the east and south east) direction ($M = 5.19$; SD = 12.51), E + SEc (cyclonic situation from the east and south-east) direction ($M = 5.20$; $SD = 9.61$) and N + NEa(anti-cyclonic situation from the north and north-east) ($M = 4.90$; SD = 13.62), from which cold polar continental air usually flows in (Fig. 4).

A one-way analysis of variance again revealed that there was a statistically significant correlation between daily hazel pollen count and the type of air mass flow $p < 0.001$ (Table 8). Multiple comparisons showed that the highest average hazel pollen count was noted in the case of wmP (warm maritime polar air) ($M = 23.99$; SD = 38.39) and the lowest one was recorded in the case of *T* (tropical air) ($M = 3.78$; SD = 6.70), being very rare during pollen seasons (0.71%), and *A* (arctic air) (M = 4.71; SD = 9.02), the frequency of which in the hazel pollen season amounted to 13.68% (Fig. 5).

A backward linear regression model was developed to summarize all results and analyse the impact of weather conditions on the concentration of hazel pollen grains (Table 9). This method allows for separating variables that have the strongest impact on daily hazel pollen count. Therefore, the model includes variables that do not strongly correlate with each other and describe the phenomenon studied in a universal manner.

The model of the impact of weather variables on the daily hazel pollen count proved to be statistically

Table 6 Analysis of variance of daily hazel pollen count by front type

Front type	Frequency %	Hazel pollen count *M* (± SD)
No front	55.11%	9.54 (± 20.34)
Warm	11.87%	15.29 (± 33.62)
Cold	16.35%	11.4 (± 21.06)
Occluded	5.27%	8.99 (± 16.77)
Stationary front	5.27%	7.1 (± 14.82)
Various fronts	6.13%	11.09 (± 25.7)
P		0.065

M—average. SD—standard deviation. *P*—statistical significance

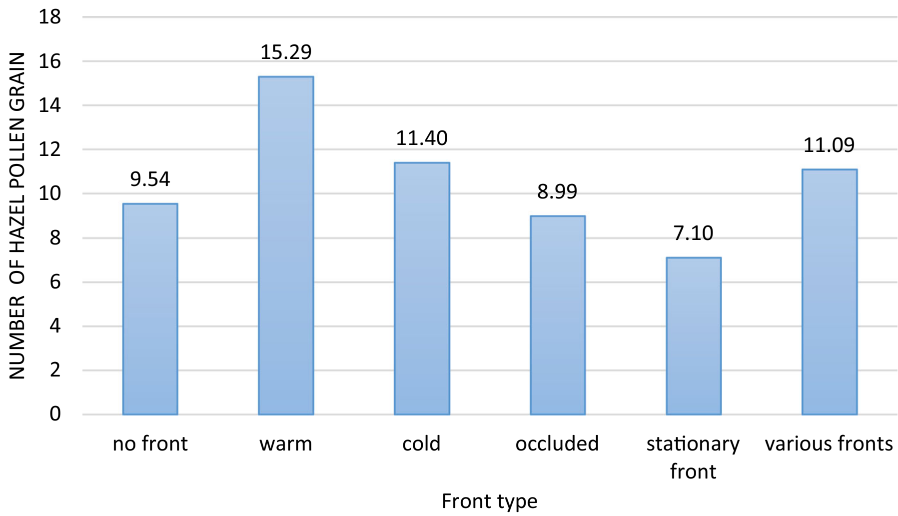

Fig. 3 Average number of hazel pollen grains broken down into weather front type

Table 7 Results of the analysis of variance of the daily hazel pollen count on account of the air mass inflow direction

Direction	Frequency %	Hazel pollen count *M* (± SD)
N + Nea	7.23%	4.9 (± 13.62)
E + Sea	10.14%	5.19 (± 12.51)
S + Swa	5.42%	20.52 (± 27.09)
W + NWa	14.54%	13.44 (± 26.62)
Ca + Ka	12.03%	7.8 (± 17.23)
N + Nec	5.74%	8.86 (± 14.34)
E + Sec	6.60%	5.2 (± 9.61)
S + SWc	9.67%	19.49 (± 35.86)
W + NWc	15.80%	11.87 (± 25.6)
Cc + Bc	10.93%	6.73 (± 12.09)
X	1.89%	12.13 (± 26.52)
P		$p < 0.001$

M—average. SD—standard deviation. ***$p < 0.001$

Anticyclonic situations: N + NEa, E + SEa, S + SWa, W + NWa, Ca + Ka, Ca—central anticyclone situation (high centre), Ka—anticyclonic wedge or ridge of high pressure. Cyclonic situations: N + NEc, E + SEc, S + SWc, W + NWc, Cc + Bc, Cc—central cyclonic, centre of low, Bc—trough of low pressure (different directions of air flow and frontal system in the axis of through). *x* undefined type. The letters: N, NE, E, SE, S, W, NW, SW indicate the directions of air mass inflow

significant $F(5.1207) = 21.67$; $p < 0.001$; $R^2 = 0.08$. The variation of weather conditions of 8% explained the variation of daily hazel pollen count (Table 9).

The following weather conditions proved to be statistically significant predictors of hazel daily pollen count: maximum temperature $t = 7.09$; $p < 0.001$; $\beta = 0.35$, near-the-ground temperature $t = -3.47$; $p < 0.01$; $\beta = -0.16$, sunshine hours $t = -1.99$; $p < 0.05$; $\beta = -0.08$, maximum wind speed $t = 4.11$; $p < 0.001$; $\beta = 0.12$ and snow cover depth $t = -2.03$; $p < 0.05$; $\beta = -0.06$ (Table 10). Maximum temperature and maximum wind speed had a positive effect on hazel daily pollen count. Other variables had a negative effect. Maximum temperature was the most powerful predictor for daily hazel pollen count. With the increase in the maximum temperature by 1°, hazel pollen count grew on average by $B = 1.24$ (Table 10).

Correlation analysis showed that SPI depended not only on weather conditions in the season, but also on the ones in the preceding year. SPI was correlated with maximum temperature $r = 0.51$; $p < 0.05$, minimum temperature $r = 0.54$; $p < 0.05$, near-the-ground temperature $r = 0.42$; $p < 0.05$ and average temperature $r = 0.62$; $p < 0.01$ in a positive and statistically significant manner. High average values of these variables in the years studied correlated with a higher SPI in the pollen season (Table 11). In contrast, statistically significant negative correlations were observed in the case of precipitation $r = -0.42$; $p < 0.05$ and snow cover depth $r = -0.41$; $p < 0.05$ (Table 11).

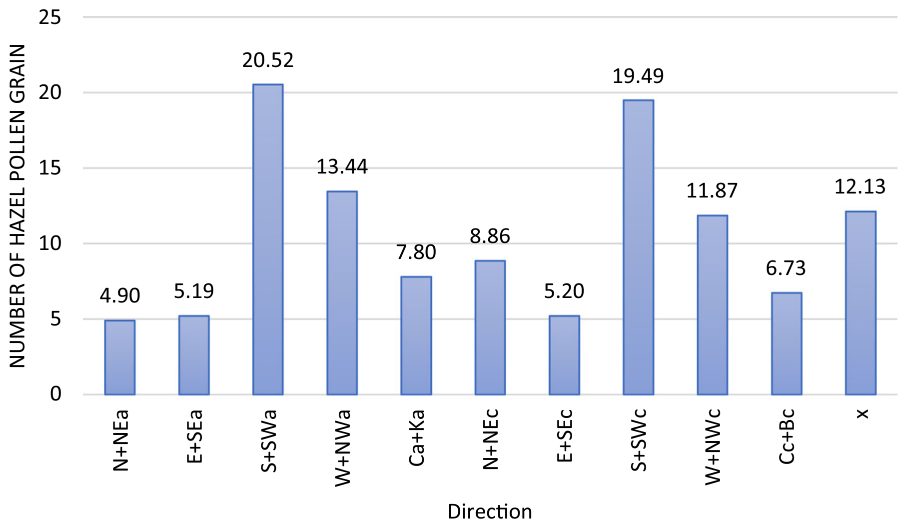

Fig. 4 Average number of hazel pollen grains broken down into the direction of air mass inflow. Anticyclonic situations: N + NEa, E + SEa, S + SWa, W + NWa, Ca + Ka, Ca—central anticyclone situation (high centre), Ka—anticyclonic wedge or ridge of high pressure. Cyclonic situations: N + NEc, E + SEc, S + SWc, W + NWc, Cc + Bc, Cc—central cyclonic, centre of low, Bc—trough of low pressure (different directions of air flow and frontal system in the axis of through), *x*—undefined type. The letters: N, NE, E, SE, S, W, NW, SW indicate the directions of air mass inflow

Table 8 Analysis of variance of daily hazel pollen count by air mass type

Air mass type	Frequency %	Hazel pollen count *M* (± SD)
A	13.68%	4.71 (± 9.02)
mP	13.36%	9.89 (± 15.47)
omP	27.83%	8.3 (± 18.37)
cP	18.08%	7.76 (± 18.27)
wmP	13.92%	23.99 (± 38.39)
T	0.71%	3.78 (± 6.7)
v.a.m	12.42%	11.42 (± 23.73)
P		$p < 0.001$

M—average, SD—standard deviation, $***p < 0.001$

omP—old-maritime polar air (transformed), wmP—warm maritime polar air, fmP—fresh maritime polar air, cP—continental polar air, *A*—arctic air, *T*—tropical air, v.a.m.—various air masses at the fronts

As far as weather conditions with effect on SPI in a year preceding the pollen season are concerned, the highest correlation coefficients were noted in the case of temperatures from July to September (Table 12). A statistically significant positive correlation was also demonstrated in the case of sunshine hours $r = 0.46$; $p < 0.05$, precipitation $r = 0.50$; $p < 0.05$ and relative humidity $r = 0.48$; $p < 0.05$ in the period from July to September in a year preceding the pollen season (Table 12).

The duration of hazel pollen season showed a positive correlation with precipitation $r = 0.51$; $p < 0.05$ and snow cover depth $r = 0.49$; $p < 0.05$, and a negative correlation with maximum temperature $r = -0.56$; $p < 0.05$, minimum temperature $r = -0.62$; $p < 0.01$, near-the-ground temperature $r = -0.49$; $p < 0.05$, average temperature $r = -0.59$; $p < 0.05$ and sunshine hours $r = -0.58$; $p < 0.05$ (Table 13). No significant correlations were demonstrated between duration of hazel pollen seasons, air flow directions, and types of air masses and weather fronts.

4 Discussion

Both weather conditions while flowering and flower bud formation and genetic determinants of plants related to their productivity have impact on the course of pollen seasons. The longer the series of measurements is, the more complete data can be obtained about the dynamics of pollen seasons of individual taxa. The variation of the beginning of hazel pollen seasons is one of the highest among early-flowering

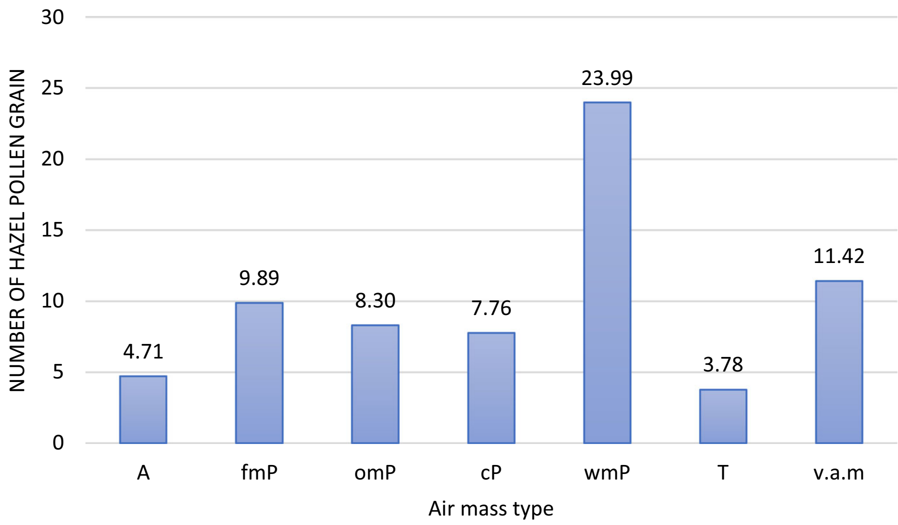

Fig. 5 Average number of hazel pollen grains broken down into the direction of air mass inflow, omP—old-maritime polar air (transformed), wmP—warm maritime polar air, fmP—fresh maritime polar air, cP—continental polar air, *A*—arctic air, *T*—tropical air, v.a.m.—various air masses at the fronts

Table 9 The results of the regression analysis for the impact of weather conditions on the daily hazel pollen count

	D*f*	*F*	*p*	R^2
Regression	5	21.67	0.000	0.08
Remainder	1207			

df—number of degrees of freedom. *F*—analysis of variance. *P*—statistical significance. R^2—coefficient of determination

trees (Dąbrowska 2008; Myszkowska et al. 2010; Puc and Kasprzyk 2013; Stępalska et al. 2016). The studies presented confirm this variation and indicate that the occurrence of hazel pollen in the air of Sosnowiec may vary significantly between years, even by 2 months. It is therefore important to be able to accurately predict the beginning of the hazel pollen season so that individuals and healthcare employees could plan strategies for treating allergies. The early flowering of trees, such as hazel, is highly dependent on the temperature in the period prior to pollen shedding (Emberlin et al. 2007; Grewling et al. 2014; Kalinovych et al. 2016; Stępalska et al. 2016; Filbrandt-Czaja and Adamska 2018; Dąbrowska-Zapart et al. 2018). In Sosnowiec, the first hazel pollen grains may appear in the air in the first half of January, if average temperatures before the season are high (Table 4). In contrast, long frosty winters may delay the beginning of the hazel pollen season. In such case, pollen of this taxon appears in Sosnowiec only at the beginning of

Table 10 The results of the regression analysis for the impact of weather conditions on the daily hazel pollen count

Hazel pollen count	*B*	SE	*β*	*t*	*p*
(Constant)	− 4.37	2.19		− 2.00	0.046
Maximum temperature	1.24	0.18	0.35	7.09	0.000
Near-the-ground temperature	− 0.74	0.21	− 0.16	− 3.47	0.001
Sunshine hours	− 0.46	0.23	− 0.08	− 1.99	0.047
Maximum wind speed	1.92	0.47	0.12	4.11	0.000
Snow cover depth	− 0.24	0.12	− 0.06	− 2.03	0.042

B—non-standardized coefficient. SE—standard error. *B*—non-standardized coefficient. *t*—t-Student test. *P*—statistical significance

Table 11 The results of Pearson's r correlation between the SPI of hazel and the weather conditions for annual data

Weather conditions	Seasonal pollen index (SPI) of hazel
Precipitation	− 0.42*
Snow cover thickness	− 0.41*
Average wind speed	0.39*
Maximum wind speed	0.37
Maximum temperature	0.51*
Minimum temperature	0.54*
Near-the-ground temperature	0.42*
Average temperature	0.62**
Sunshine duration	0.33
Humidity	0.26

$p < 0.05$*; $p < 0.01$**; $p < 0.001$***

Table 12 Correlation coefficients between meteorological elements in the year preceding pollination and the SPI of hazel pollen grains

Weather conditions	Seasonal pollen index (SPI) of hazel
Precipitation July–September	0.50*
Average wind speed July–September	− 0.20
Maximum wind speed July–September	− 0.24
Maximum temperature July–September	0.52*
Minimum temperature July–September	0.71**
Near-the-ground temperature July–September	0.68**
Average temperature July–September	0.80***
Sunshine duration July–September	0.46*
Humidity July–September	0.48*

$p < 0.05$*; $p < 0.01$**; $p < 0.001$***

Table 13 The results of Pearson's r correlation between the pollen season duration and the weather conditions

Weather conditions	Duration of the pollen season
Precipitation	0.51*
Snow cover thickness	0.49*
Average wind speed	0.41
Maximum wind speed	0.42
Maximum temperature	− 0.56*
Minimum temperature	− 0.62**
Near-the-ground temperature	− 0.49*
Average temperature	− 0.59*
Sunshine duration	− 0.58*
Relative humidity	0.40

$p < 0.05$*; $p < 0.01$**; $p < 0.001$***

March. The difference between the earliest (the 10th of January 2007) and the latest (the 14th of March 2005) appearance of hazel pollen in Sosnowiec was over 2 months (Table 1). This was related to the temperature before the pollen season. It was demonstrated that high temperatures in the months preceding pollen shedding (January–February) speed up the beginning of seasons of the taxon studied. January 2007 had the highest average temperature among the years studied (3.6 °C), which undoubtedly resulted in a very early occurrence of hazel pollen in the air. In 2005, being a year with the latest beginning of the hazel pollen season, the average temperature in January was relatively high (0.3 °C), but it fell substantially in February (− 3.2 °C). Hazel pollen season began late in 2003 and 2012, which was due to low temperatures in January and February.

It is worth emphasizing that not only the temperature immediately before the season has an impact on the beginning of such season, but also in the summer in the preceding year. The highest correlation coefficients were observed for average temperatures recorded during 180 and 210 days. This means that temperatures in the period starting from the previous summer (June–August) to the pollen-shedding day play the most crucial role (Table 3). The higher the average temperature during this period, the earlier hazel starts shedding pollen. According to numerous authors, temperature in the period preceding pollen shedding has a significant impact on the beginning of the pollen season of trees that start shedding pollen at the turn of winter and spring (Frenguelli et al. 1991; Frei, 1998; Rodriguez-Rajo et al. 2004; Emberlin et al. 2007; Kim et al. 2011; Piotrowska-Weryszko 2013; Filbrandt-Czaja and Adamska 2018; Kubik-Komar et al. 2018). Also statistically significant correlation coefficients were demonstrated for relative humidity 25–30 days before the season and sunshine hours − 180 to 210 before the season (Table 3).

The term cumulative temperature sum is sometimes used while predicting the beginning of the pollen seasons of trees (Garcia-Mozo et. al. 2000; González-Parrado et al. 2006; Piotrowska and Kubik-Komar 2012; Linkosalo et al. 2017). According to this method, thecae open only after absorbing a specific amount of thermal energy (cumulative temperature), which differs among various taxa of trees. It consists in creating a cumulative series, most often from the 1st of January given year, as a sum of average daily temperatures over pre-specified thresholds from the day determined as the beginning of the pollen season.

As air temperature has undoubtedly the greatest impact on the appearance of hazel pollen grains in the air, cumulative temperatures were determined from the 1st of January to the day of the beginning of the season. Two temperature thresholds were applied: over 0 °C and over 5.5 °C. Hazel pollen appeared in the air when the sum of average temperatures higher than 0 °C and 5.5 °C amounted from 11.1 to 84.9 °C and even from 0 °C to 65.7 °C, respectively. Temperature sums falling in such large ranges do not allow for unambiguous prediction of the beginning of the pollen hazel season in Sosnowiec. It can be concluded that differences in hazelnut pollen seasons and difficulties in predicting the pollen season using the cumulative temperature sum in Sosnowiec may originate from long-distance transport from the areas where the vegetation grows earlier (Kalinovych et al. 2016).

It was demonstrated that snow cover plays an important role in the course of hazel pollen seasons. Maximum concentrations of pollen grains of this taxon were observed in all years only after snow cover completely disappeared. High concentrations were noted from a few to several days after its disappearance. Low temperature and snowfall are the most important factors determining low pollen grain concentration, in particular, if hazel crown snow-load is large.

The daily concentration of hazel pollen grains in Sosnowiec was also dependent on weather conditions. The relationship between the daily concentration of hazel pollen grains and weather conditions was also investigated by other authors (Myszkowska et al. 2007; González Parrado et al. 2009; Puc and Kasprzyk 2013; Dahl et al. 2013; Stępalska et al. 2016; Borycka and Kapsrzyk, 2018; Bruffaerts et al. 2018). Correlation coefficients noted for data in Sosnowiec turned out to be low and explain the variation of daily concentration levels depending on weather conditions only to a small extent. This may be due to the delayed effect of individual weather elements on the shedding of hazel pollen (Nowosad et al. 2018). Furthermore, pollen grain production and distribution are a complex process affected by various factors, such as weather, ecological, phenological and genetic factors (Puc 2012; Nowosad 2016).

Statistically significant and positive correlation coefficients were demonstrated for maximum, minimum, near-the-ground and average temperature as well as for sunshine hours, average and maximum wind speed in the pollen season (Table 5). Negative correlation coefficients were observed for snow cover depth and relative humidity of the air. This means that daily concentrations of hazel pollen grains were bound up with daily temperatures. A drop in daily temperature led to a decrease in the air pollen count. The presence of snow cover and high relative humidity adversely affected the appearance of hazel pollen grains in the air.

In addition to weather elements listed above, the daily concentration of hazel pollen was also affected by types of weather fronts and air masses, and their flow direction (Tables 6, 7, 8). According to Laaidi (2001), type of atmospheric circulation (cyclonal or anticyclonal) may have impact on hazel pollen concentration. The author suggests that higher pollen grain concentrations are noted in the case of anticyclonal circulation. However, the concentration of hazel pollen grains in Sosnowiec was not affected by the type of atmospheric circulation, but instead by the flow direction and type of air masses. Highest and lowest hazel pollen grain concentrations were noted when air masses were moving from S + Swa (anticyclonic situation from the south and south west) or S + SWc (cyclonic situation from the south and south west) direction and N + NEa (anticyclonic situation from the north and north-east) or E + SEc (cyclonic situation from east and south east) direction, respectively (Fig. 4). Warm maritime polar air was the air mass that exceptionally promoted high daily hazel concentrations (Fig. 5). Analysis of variance for the type of weather front showed that the warm front is favourable for high concentrations of hazel pollen grains. Thus, during a warm front the largest number of grains is recorded in the air (Fig. 3).

A backward linear regression model was developed to analyse the impact of weather conditions on hazel pollen seasons (Table 9). However, the variation in the daily number of pollen grains can be explained by the variation of weather conditions only in 8%. Maximum temperature was the most powerful predictor for hazel pollen grain concentration. With the increase in the maximum temperature by 1 degree Celsius, hazel pollen concentration grew on average by $B = 1.24$. Regression models of hazel pollen grains have also been studied by Ranta and Satri (2007), but they obtained a very low coefficient of determination, as in Sosnowiec. But the multiple regression model proposed by Puc (2007) indicated minimum temperature and average wind speed as the main weather elements that condition the presence of pollen grains in the air.

SPI of hazel did not significantly differ in the study years, as indicated by a low coefficient of variation (Table 2). However, a minor but statistically insignificant decrease in SPI was noted (Fig. 2), while a slight increase in annual hazel pollen count was observed in Szczecin (Puc 2007) and Poznań (Grewling et al. (2014)). Relatively low SPI, despite high pollen production by inflorescence, may result from frosts often taking place when hazel is flowering (Dyakowska 1937; Piotrowska-Weryszko 2001).

Numerous studies demonstrate that the SPI of some trees depends on weather elements, not only during the pollen season, but also on the ones noted one or even two years before this season (Sarvas 1972; Rodkiewicz 1973; Norris-Hill 1998; Rasmussen 2002; Ranta and Satri 2007; Stach et al. 2008). As far as weather conditions with effect on annual hazel pollen counts in Sosnowiec in a year preceding the pollen season are concerned, the highest correlation coefficients were noted in the case of temperatures from July to September (Table 12). A particularly high correlation coefficient was demonstrated for average temperatures $r = 0.80$; $p < 0.001$. A statistically significant and positive correlation was also demonstrated for sunshine hours, precipitation and relative humidity from the same period (Table 12).

SPI of the taxon discussed depended also on the temperature in the season (a particularly high correlation coefficient was demonstrated for average temperatures $r = 0.62$; $p < 0.01$) (Table 11), precipitation and snow cover depth. A positive correlation coefficient means that high temperatures in a pollen season promote a large SPI of hazel pollen grains. In turn, a negative correlation coefficient with precipitation and snow cover depth indicates their negative impact on the studied property of the pollen season.

The duration of hazel pollen seasons was correlated positively with the relative humidity of the air and snow cover depth in the season and negatively with temperatures and sunshine hours in the season (Table 13). According to Jabłoński and Szklanowska (1997), pollen is shed most intensively at low relative humidity and high air temperature. If the weather is warm and sunny, the pollen season lasts for a short time and is very regular. Low temperature and precipitation extend the flowering period and disrupt its regular course. In extreme cases, concentration of pollen grains decreases because thecae are underdeveloped. This hypothesis was confirmed in studies conducted in Sosnowiec. Statistically significant and negative correlations were demonstrated for maximum, minimum, near-the-ground and average temperature as well as for sunshine hours. Hazel was producing pollen for a shorter time when air temperature and sunshine hours were high. On the other hand, negative correlations were noted for precipitation and snow cover depth, which means that high values of these weather elements resulted in a reduced duration of the hazel pollen season.

No significant correlations were demonstrated between the duration of hazel pollen seasons, air flow directions, and types of air masses and weather fronts.

The number of days with threshold pollen grain concentrations which cause allergic symptoms varied over 23 years. The highest numbers of days with threshold concentrations causing first allergic symptoms, i.e. 35 grains in one cubic metre of air, were noted in 2001, 2002 and 2005 (Table 1)). In contrast, concentrations resulting in symptoms in all individuals hypersensitive to hazel pollen, i.e. 80 grains in one cubic metre of air, were observed in 2004, 2006 and 2011 (Rapiejko et al. 2004). These seasons were particularly burdensome for all individuals allergic to hazel pollen.

5 Conclusions

The date of the beginning of the pollen season and the maximum daily concentration level proved to be the most variable properties of hazel pollen seasons in the study period. This is demonstrated by a high coefficient of variation and large standard deviation. While the dates of the end of the season, the dates of maximum daily pollen concentration and the SPI were the least varied.

It was demonstrated that weather conditions have an impact on differences observed in subsequent hazel pollen seasons. The beginning of the pollen season depended mainly on the temperature in the months preceding this season. High temperatures in January and February speed up the appearance of hazel pollen in the air. There are positive correlations with temperatures and sunshine hours long before the season, i.e. 210–180 days before.

The daily hazel pollen concentration in Sosnowiec showed a positive and statistically significant correlation with air temperature, sunshine hours, and average and maximum wind speed. Negative correlation was demonstrated for snow cover depth and the relative humidity of the air. The daily concentration level depends also on the type of weather front as well as direction of air mass flow and its type. Analysis of variance revealed that the highest and lowest hazel pollen grain concentrations were noted when air masses were moving from S + SWa or S + SWc and E + SEa, E + SEc or N + NEa, respectively, the latter one being associated with cold, polar continental air. Warm, maritime polar air was the air mass that exceptionally promoted high daily hazel concentrations.

A backward linear regression model was developed to summarize all results and analyse the impact of weather conditions on daily hazel pollen concentration. The model of the impact of weather elements on hazel pollen count proved to be statistically significant, but variation of weather conditions explained the variation of pollen grains only in 8%.

SPI of hazel pollen grains was correlated with conditions during the season and in the preceding season. Statistically significant negative correlation coefficients were demonstrated for precipitation and snow cover depth in the season, and positive correlation coefficients were noted for average, maximum, minimum and near-the-ground temperature. As far as conditions in the year preceding the pollen season are concerned, high positive correlation coefficients were also observed in the case of thermal conditions, sunshine hours, relative humidity and precipitation from July to September.

The duration of the hazel pollen season depends on precipitation, snow cover depth and temperature in a given season. A statistically significant and positive correlation was demonstrated for the two first weather elements, and negative correlation was observed for maximum, minimum, near-the-ground and average temperature.

The highest numbers of days with threshold concentrations causing first allergic symptoms, i.e. 35 grains in one cubic metre of air, were noted in 2001, 2002 and 2005. In contrast, concentrations resulting in symptoms in all individuals hypersensitive to hazel pollen, i.e. 80 grains in one cubic metre of air, were observed in 2004, 2006 and 2011.

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