Description of the main Poaceae pollen season using bi-Gaussian curves, and forecasting methods for the start and peak dates for this type of season in Rzeszów and Ostrowiec Św. (SE Poland)

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Grasses characteristically produce a huge amount of small pollen grains, which pose a risk to allergy sufferers. In many aerobiological studies, great variations in the behaviour of the grass pollen season are stressed. We state that in Rzeszów and Ostrowiec Św. there is some regularity in the pattern of the main grass pollen seasons, which is clearly double-peaked. The aim of our work was to elaborate the algorithm which defines the main grass pollen season. Next, the null hypothesis was tested about the lack of difference between daily pollen concentrations and meteorological parameters. Grass pollen seasons were defined using the method of fitting two bell curves. The estimated grass pollen season is characterised by two periods of high or relatively high concentrations, separated by a period of low concentration. In order to investigate the time dependence of the correlation between pollen concentration and the weather parameters, the Gaussian-weighted correlation coefficient has been calculated. Maximum temperature, mean temperature and sunshine positively correlated with pollen concentrations, but relative air humidity and rainfall on the previous day had a negative effect. The temperatures of the second and third ten-day periods of April were the best independent variables for forecasting the beginning and peak dates of the main pollen seasons. An analysis of the results shows that the pattern of successive flowering in grass species and meadow cutting dates appear to be the factors which cause the characteristic bimodal behaviour of the grass pollen season.

Introduction

Grasses (Poaceae) are one of the most important families of flowering plants, in spite of the fact that they appeared relatively late in phylogenetic development (Cretaceous period).[1] This family comprises 600–800 genera and 8000–10 000 species. They are characterised by an extensive number of ecotypes, polyploids and hybrids and tolerate a wide range of environmental conditions.[2] Grass pollen is one of the most frequent and serious causes of pollen allergy in central and western Europe.[3,4] The hourly and daily pollen concentrations are normally very high and pollen seasons may last quite long—up to several weeks.[5–12] Grasses are characterised by a huge production of small pollen grains which can be transported for several hundred or even thousands of kilometres by large air masses.[13] Pollen production is under genetic and physiological control, but environmental factors—especially weather and habitat conditions—are governed by yearly variations.[14,15] Within the Poaceae family, pollen-grain production per anther ranges from the dozens (*Briza minor*—little quaking grass[16]) to the tens of thousands (*Secale cereale*—rye;[15] *Arrhenatherum album*—tall oat grass[14]). Pollen production and the mechanism of dispersal can even vary between close genera.[17] Perennial species commonly produce more grains than annual ones;[3,14] Aboulaich *et al.*[16] reported around 4.25 times more, on average. Only a few species are characterised by high pollen production and/or number of inflorescences per individual plant which could be large enough to pose a risk to allergy-sufferers.

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Environmental impact

Grass pollen is one of the main causes of pollen allergy in Europe. Airborne grass pollen concentrations are characterized by highly seasonal variations. Photoperiodicity, temperature and rainfall influence pollen production. In Rzeszów, daily pollen concentrations mainly depended on temperature and air humidity. The grass pollen season had a bimodal pattern. It was described by the method of fitting two bell curves. This characteristic behaviour was greatly influenced by weather, the flowering phenology of commonly occurring species and haymaking. The presented models more accurately forecast the time of maximum concentrations than the daily concentrations and the start of the pollen season. Continuous aerobiological monitoring and the development of the forecasting models are important for the proper diagnosis and treatment of allergies.

The environmental factors which occur prior to the flowering phase of grasses often determine the level of airborne pollen that later exists. Laaidi[25] described them as the primary factors. Development of a flower bud begins when the diurnal dark period reaches a length which is adequate for that species. Therefore, development and pollen release are quite predictable events.[26] The time period of pollen development is genetically programmed, and to a lesser degree influenced by the environment.[27] Water availability and temperature have a highly positive influence on grass development, pollen production and anthesis. Pollen production is also positively correlated with rainfall in the months prior to flowering.[18,28] Jato *et al.*[24] claimed that increasing temperatures and drought in the period preceding the pollen season may partly influence the decline of yearly grass pollen counts. Pollen production on days with extremely high or low temperatures may be a limiting factor, and temperatures of around 20–25 °C are the most favourable.[5,29] Each species of the Poaceae family responds differently to meteorological factors.[20,29,30] Generally, rainfall and high air humidity inhibit anthesis,[28,31] but as Reddi *et al.*[20] reported, *Dactylis* spp., *Phelum* spp., and *Alopecurus* spp. are less sensitive to rainfall. Secondary meteorological factors such as temperature, light intensity, air humidity, and rainfall determine the opening of anthers and pollen release.[25,29,31] Wind-pollinated grasses dehisce their anthers under dry conditions and immediately shed their pollen into the air and onto surrounding surfaces.[32] Airborne pollen behaves as a function of wind velocity, atmospheric turbulence, anther height above the surrounding surface, and density of the surrounding vegetation.[33] Maximum temperature, rainfall and air humidity are the meteorological parameters which strongly influence daily counts.[18,23,34] Weak wind speed involves pollen shedding. If it flows from the direction of the pollen source, airborne pollen counts increase. Greater wind speed leads to a dilution in airborne pollen concentrations.[26,33] Strong wind frequently occurs with showery weather. When rain falls, pollen is washed out of the air. Pollen grains can serve as condensation nuclei for raindrops and are then deposited on wet surfaces at ground level.[23] Warmer weather in early months of the year encourage grass growth and early maturation of flowers. This can generate a long period of low pollen counts at the beginning of the atmospheric pollen season before the main flowering period. Temperatures above 25 °C limit grass pollen production, and lower airborne pollen concentrations are noted.[5,23,29] It should be stressed that meteorological parameters correlate with each other and jointly, all of them create types of weather which affect pollen counts.

Climate, topography and type of land use are cited as reasons for differences in atmospheric pollen seasons.[5,9,34,35,36] In Spain, the local climate determines the character of the grass pollen seasons. In coastal climates, the grass pollen season begins three weeks later than in inland areas.[6] Valencia-Barrera *et al.*[37] report that grass pollen seasons appear to behave similarly, even in cities located on different continents (Montréal, Canada; León, Spain), if the bioclimatic indicators of these regions are similar. Large-scale air mass phenomena like the North Atlantic Oscillation (NAO) may also affect airborne grass pollen data. The NAO explains the yearly variations in temperature to a significant degree. The influence of the NAO on timing and severity of atmospheric season, annual pollen counts, and through its affect on temperature and precipitation, varies spatially. In the positive phase of the NAO in northern Europe, winters are warm and wet and the growing season starts earlier, whereas in central and southern Europe winters are drier.[38] In aerobiological investigations, the local and regional flora, vegetation and type of land use should be taken into consideration.[39] Anemophilious airborne tree pollen represents regional forest vegetation and herbaceous airborne pollen reflects the local type.[40] In towns, pollen sources are limited. High buildings limit pollen dispersal, especially herbaceous pollen. In Spain, pasture areas are recognized as the main source of airborne grass pollen and as high-risk areas for allergy sufferers in June and July.[41]

Variations in pollen concentrations and patterns within a pollen season correspond with different floral phenophases. The analysis of phenological data makes it possible to determine which species may be responsible for the characteristics of the pollen season.[42,43] The relationship between flowering phenology and airborne pollen was confirmed *e.g.* for *Betula* (birch) and *Quercus* (oak).[44,45]

In many aerobiological studies, a high variability in the pattern of the daily and hourly counts is observed, and the number of peaks and dates of their occurrence are stressed.[18–20] Because we can not identify pollen grains by their species or even genera, the grass pollen season is very long, dispersed, and pollen season dates are difficult to forecast.[21,22] In Szczecin, (northern Poland) the Poaceae pollen season lasts about three months with several peaks.[23] In several cities in Catalonia, (NE Spain) two-to-three week lags between the dates of peaks and the highest variation in the Poaceae annual pollen sums were observed but the curves illustrating pollen seasons were generally similar in shape and seasonality.[8] A long, but unimodal (one peak) season is characteristic in Lugo and Querence, NW Spain.[24]

The authors state that in Rzeszów and Ostrowiec Św. there is some certain regularity in the pattern of the main grass pollen season, which is clearly double-peaked. The aims of this work were to explain the algorithm which describes the main grass pollen season, and to estimate which of the selected environmental elements may be related to the characteristic behaviour of the Poaceae pollen season. Initially, the relationship between weather and pollen counts was measured by methods that were not presented in other aerobiological papers—the bimodal probability and Gaussian-weighted moving correlation coefficient. The next step was to use the Spearman method to test the null hypothesis against the lack of differences between daily pollen concentration and meteorological parameters. The following environmental factors that were considered were the annual cycle of flowering of grass species and anthropogenic treatment. The vital aim was to produce forecasting methods for the start and peak dates of the main pollen season.

Materials and methods

Studies were conducted in two towns in south-eastern Poland: Rzeszów and Ostrowiec Św. (Fig. 1). In Rzeszów, aerobiological monitoring was conducted for the years 1997–2005 and in 2007, and in Ostowiec Św. in 1995–1996. Rzeszów (50°01′N; 22°02′E) is located at an altitude of 200 m above sea level, and in this region altitude differences range from 80–200 m above sea level. The city is situated in a region where very warm days with

Fig. 1 The location of the two aerobiological monitoring sites used in this study.

precipitation occur relatively frequently, as well as days with ground frost conditions and relatively cool or very cool sunny weather. There are relatively few cool days with precipitation and high cloudiness.[46] For the years 1997–2005 the mean annual temperature was 8.6 °C and mean annual precipitation was 712 mm. Mean temperatures for July (the warmest month) and January (the coldest month) were 19 °C and −2.1 °C, respectively. In this region, westerly, north-westerly and south-westerly winds predominate. During the year there are roughly 230 days with transformed maritime air masses.[47]

Rzeszów is a town of approximately 180 000 people and typical urban development. Its flora and vegetation are under strong human pressure, and most plant communities are anthropogenic. In the close proximity of the pollen trap there are semi-natural and synanthropic meadows with *Alopecurus pratensis* (meadow foxtail) and *Arrhenatherum elatior* (tall oatgrass) as the dominant species. The urbanization index (UI) of the town is 0.54 (UI is the amount of built-up and industrial area within the investigated territory divided by the total area in question). Within the town and its surroundings, forests cover 21.6% of the total area, whereas agricultural land is 59.3%, with 15.9% consisting of meadows and pastures.[48] Wheat and potato are the main crops. There are also hay-growing meadows, pastures, and apple and blackcurrant orchards. The most frequent types of forest are pine, mixed and oak–hornbeam.

Ostrowiec Św. (50°94′N; 21°39′E) is situated about 120 km to the north of Rzeszów. It is a town of approximately 80 000 people partially located in the Kamienna River valley. The town is situated in a climatic region which is characterised by relatively few days with relatively warm weather.[46] The synanthropic vegetation patches and a city park are found in close vicinity to the trap site. The agricultural lands of the Ostrowiec Św. district cover 53% of the total area, with 5.4% consisting of meadows and pastures. Forests, mainly pine and mixed, occupy over 30% of the area within the district.[49]

In Rzeszów and Ostrowiec Św., the aerobiological studies were carried out using the volumetric method in the period from 1 January to 31 October. Pollen traps (Burkard, Lanzoni VPPS-2000) were placed on the roofs of the buildings at a height of 12 and 30 m, respectively. A microscope slide was prepared for each day and the pollen grains were identified and counted using 400× magnification from twelve vertical bands. The results were expressed as the average daily number of pollen grains in 1 m^3 of air.

The phenological observations from Rzeszów in the years 2003–2004 were carried out using the Łukaszewicz method.[50] The dates of the main flowering period were noted. It started when approximately 25% of flowers had opened and lasted until approximately 75% of flowers were overblown. Grass species common to the flora of the town[51] were observed: *Poa annua* (annuals bluegrass), *Alopecurus pratensis* (meadow foxtail), *Anthoxanthum odoratum* (sweet vernalgrass), *Dactylis glomerata* (orchard grass), *Phleum pratense* (timothy grass), *Poa pratensis* (smooth-meadow grass), and *Festuca pratensis* (meadow fescue). The observations were conducted at 5–7 day intervals at three stations located in different parts of the town. The proper vegetative and generative development of plants are mostly dependent on their environmental habitats. Temperature, insolation, water regime and competition between individuals and species greatly affect generative and vegetative plant development. In order to compare the flowering patterns, three different locations were chosen: (1) an open, sunny area, (2) in the shade of other plants, (3) in a dense building complex. As mentioned above, human activity may influence pollen concentrations and the pollen season. The data from hay cutting was the next factor taken into consideration. The harvesting dates were obtained from one experimental agricultural station of the University of Rzeszów located in the village of Krasne, about 7 km from the pollen trap (UI = 0.01).[48] It was assumed that hay cutting took place during the same period of time in the vicinity of Rzeszów.

The atmospheric pollen seasons were determined using two methods: (1) the percentage method (98%), and (2) determined by the mathematical function presented below. The start of the pollen season defined by the percentage method was the day on which the cumulative sum of pollen grains reached the value of 1% of the seasonal total, whereas the day on which the cumulative sum reached the value of 99% was considered to be its end. The text refers to the SPI symbol, which means the total number of pollen grains in the atmospheric grass pollen season. In addition, the atmospheric grass pollen seasons had a characteristic pattern, and in order to describe this quantitatively, the method of fitting two bell curves (Gaussian curves, $\exp(-x^2)$) was applied, with location and scale parameters in a time domain, as well as amplitude parameters. This formula was tested against a description of the main Poaceae pollen season for the years 2007 and 1995–1996 in Ostrowiec Św.

Only the data from Rzeszów was used for correlation analyses between the grass pollen concentration and meteorological parameters, as there is no weather station in Ostrowiec Św. At first, the correlations between the short-term variations (the shortest possible, from day to day, and up to one and two days of lag) in the airborne pollen counts and weather conditions were examined. First, days on which at least twice as many pollen grains (an arbitrary choice) were recorded than on the previous day were observed. Next, any change in meteorological values for these pairs of days when pollen counts doubled was noted. The relationship is positive when the proportion of days is >0.5 and negative when it is <0.5. An additional control was the minimum number of grains (N) recorded on a particular day. The significance of deviation in the proportion of days with a consistent increase in all parameters was tested using the bimodal probability.

The question of correlation between pollen counts and meteorological data was also analysed by another method. In order to investigate time dependence in the correlation between pollen concentrations and weather parameters, a Gaussian-weighted moving correlation-coefficient was plotted. In this time-smoothing parameter, the σ value of the Gaussian weights was chosen as 5 days, which is the result of a trade-off between the time resolution and the statistical precision of correlation coefficients. Along with the plots of correlations, the double-peaked Gaussian model of a pollen season was given to facilitate correlation of correlations with the amount of pollen itself.

The next step was to seek the cause-and-effect relationship between the weather parameters and daily average pollen counts (in fact, the square root was taken) in phases I, II and the period of low concentration between these two. Standard multiple regression models were constructed to predict daily average pollen values for these three periods.

Linear regression was used to forecast the start and peak of the main pollen season. Variables which were reported to be significant in the literature were observed for significant influence on our calculations.[18,21,23,25] They were namely, mean and maximum temperatures, precipitation and sunshine from different periods of selected months. The model was validated for 2007. The standard of $\alpha \leq 0.05$ level of significance was used in all statistical methods.

Results

Each year the atmospheric grass pollen season was characterised by similar behaviour. The pollen season was described using the following bimodal function:

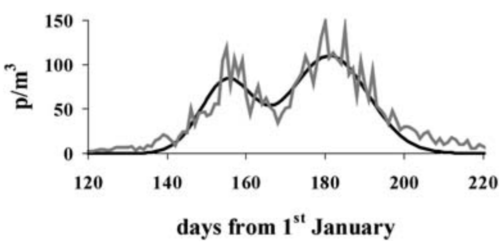

Fig. 2 Mean grass pollen concentrations for Rzeszów, in the years 1997–2005 (black line—estimated curve; p/m^3—pollen grains per m^3).

$$f(t) = a_1\exp(-0.5 \times (t - t_1)^2/s_1) + a_2\exp(-0.5 \times (t - t_2)^2/s_2)$$

where:

$f(t)$ is the daily number of pollen grains,

t is the day from 1st January,

t_1, t_2 are the day of the first and the second maximum, respectively,

a_1, a_2 are the corresponding values (amplitude) of the two maxima (pollen grains per m^3 per 24 h),

s_1, s_2 are the variances (σ^2) as a measure of the duration of the two maxima (day^2).

The presented function describes the behaviour of the pollen season well (Fig. 2). All the parameters of the functions were statistically significant, even at $\alpha \leq 0.001$. It was stated that in Rzeszów, the lowest percentage of explained variation by this algorithm was obtained for the year 2000, and the highest for 2005. For 2007, this formula explained over 77% of the variability (Table 1). The comparisons of the results from Ostrowiec Św. and Rzeszów showed great similarities, except for the maximum values (Fig. 3a, b). For 1995 and 1996, the formula explained 78% and 56% of pollen concentration variability, respectively (Table 2).

According to the applied function, the estimated main grass pollen season can be divided into the following phases: two phases of high pollen concentration: phase I, phase II, and a period of lower concentration between these phases (Fig. 2). The variations (V—variation coefficient (%)) in the estimated dates (t_1, t_2) were very small; they were larger in the case of the other estimated parameters presented in Table 1. In 2007, the differences between t_1 and the average t_1 was one day, and between t_2 and the average t_2 was eight days. The lengths (the beginning and end dates of the seasons) were characterised by relative similarity. The atmospheric pollen seasons defined by the percentage method generally started in the middle of May and lasted until the end of August. In seasons described by the above function, the estimated main pollen seasons were two-and-a-half to three times shorter than the obtained ones. In these seasons, there were about one-third fewer grains than in the atmospheric seasons determined by the 98% percentage method (Table 3). The results obtained in Ostrowiec Św. were similar to average ones (Table 4). In 2007, the dates of the beginning of the main pollen

Table 1 The estimated statistics for the Poaceae main pollen seasons in the years 1997–2005 and in 2007 (test year) in Rzeszów[a]

	t_1	t_2	a_1	a_2	s_1	s_2	length (days) of the decrease period	length (days) of the phase I	length (days) of the phase II	R^2 (%)
1997	164	184	102	279	28	9	12	11	6	72.4
1998	154	180	102	90	13	136	11	7	23	64.3
1999	158	182	236	180	7	38	15	5	12	85.1
2000	150	175	73	99	46	56	10	13	15	57.0
2001	160	189	82	157	85	42	14	18	13	67.5
2002	149	176	94	111	68	53	11	16	15	63.7
2003	155	176	110	240	40	147	3	13	24	64.2
2004	158	187	117	110	41	135	11	13	23	70.5
2005	155	184	325	161	0	102	18	1	20	87.2
average	156	181	138	159	36	80	12	11	17	
V (%)	2.9	2.8	61.5	41.4	76.7	63.6	35.6	50.4	36.7	
2007	155	173	181	136	28	39	7	9	13	77.1

[a] t_1—the time of the maximum in the phase I in days from 1st January; t_2—the time of the maximum in the phase II in days from 1st January; a_1—the value of the first maximum; a_2—the value of the second maximum; s_1, s_2—variances; R^2—determination coefficient; V—variation coefficient.

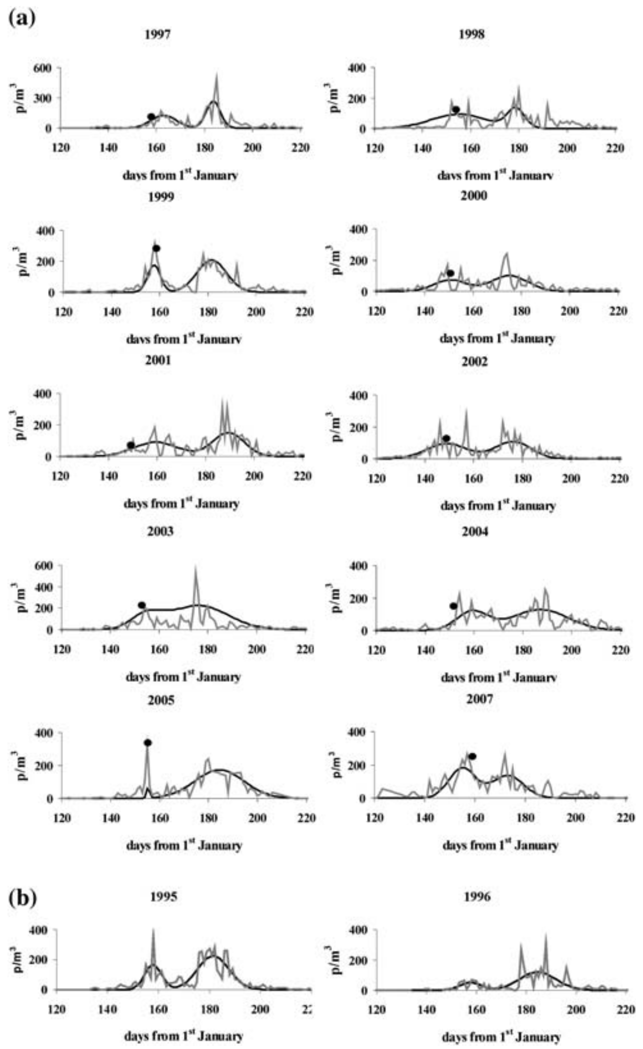

Fig. 3 (a) Seasonal occurrence of grass pollen concentrations in Rzeszów, for years 1997–2005 (black line—estimated curve; ● marks the day of the first hay cut; p/m³—pollen grains per m³). (b) Seasonal occurrence of grass pollen concentrations in Ostrowiec Św., for years 1995–1996. (black line—estimated curve; p/m³—pollen grains per m³).

season (start*) and the first peak (max I*) were the same as the average dates (Table 3).

Both in the first (2003) and second (2004) year of phenological observations, *Poa annua* (annual bluegrass) was first to bloom, *i.e.* as early as April, and the entire bloom period lasted very long—until the beginning of September. *Alopecurus pratensis* (meadow foxtail) is a species which began flowering in early May. The pollination period continued until the first ten days of June. In the middle of May, the next grass species started flowering, notably: *Dactylis glomerata* (orchard grass), *Poa pratensis* (smooth-meadow grass), and *Anthoxanthum odoratum* (sweet vernalgrass). The beginning of June is a period when other grasses were observed to start intensive pollination. Most of the observed species intensively flowered during phase II of the main grass pollen seasons (Fig. 4). In the case of each species, the flowering periods were synchronized among all phenological sites.

In Krasne, the first hay cuts were taken at the end of May or at the beginning of June (Table 5) in the years 1997–2005 and 2007, and from several to a dozen or so days later a decrease in pollen concentration was noted (Fig. 3a).

The cause-and-effect relationships between an increase in the number of grass pollen grains and an increase in the values of the weather parameters were quite strong. The question is if the sign of correlation agrees with our expectation. The proportion of days on which there was an increase in mean and maximum air temperature, and sunshine to pollen counts was well above 0.5 and therefore, we can say that the relationship was positive. For relative air humidity, this proportion was only around 0.3. That means that there were more days when pollen concentrations decreased with a simultaneous increase in relative air humidity; therefore it can be stated that this relation was negative. When precipitation was observed independently of other variables, it produced a weakly significant result. The number of days with a simultaneous increase in the pollen count and precipitation were similar to the numbers of days with an increase in the pollen count and a decrease in precipitation. Days which had low *N* (pollen counts), were often followed by days with a twofold increase. However, the statistical significance is small because for example, an increase from two to five grains may easily be random. When there was a higher *N*, there were a few following days when the number of grains increased. Despite that, the result was significant enough (Fig. 5). An interesting pattern is observed when a one-day lag is applied. Instead of temperature and relative air humidity, precipitation and sunshine were the most influential parameters, while during the initial day-to-day analysis precipitation was actually poorly significant. When there were two days of lag, the correlations of pollen counts with weather parameters seemed to disappear (Fig. 5). The results obtained with the use of the moving correlation coefficient methods are in accordance with the ones presented above. These methods exhibit out-of-noise variation in time (the value as well as the integer sign) which seems to be connected with the recognized phases of pollen concentration. This feature is especially clear in 2004, where the negative correlation of pollen with precipitation is mostly pronounced at both peaks of that pollen season (Fig. 6).

Table 2 The estimated statistics for the Poaceae main pollen seasons in the years 1995–1996 in Ostrowiec Św[a]

	t_1	t_2	a_1	a_2	s_1	s_2	length (days) of the decrease period	length (days) of the phase I	length (days) of the phase II	R^2 (%)
1995	158	182	167	225	11	38	14	7	12	78.1
1996	157	184	51	119	18	53	15	8	15	56.3

[a] t_1—the time of the maximum in the phase I in days from 1st January; t_2—the time of the maximum in the phase II in days from 1st January; a_1—the value of the first maximum; a_2—the value of the second maximum, s_1, s_2—variances; R^2—determination coefficient; V—variation coefficient.

Table 3 Descriptive statistics of the Poaceae atmospheric pollen seasons and estimated main pollen seasons (*) in the years 1997–2005 and in 2007 (test year) in Rzeszów[a]

	start	start*	end	end*	length (days)	length* (days)	SPI	SPI*	max I	max I*	max II	max II*
1997	18.05	05.06	15.08	06.07	90	30	4196	3178	166/11.06	13.06	491/04.07	03.07
1998	11.05	30.05	03.09	11.07	118	43	3826	2976	170/01.06	03.06	244/29.06	29.06
1999	13.05	04.06	05.09	07.07	118	34	5118	3697	317/04.06	07.06	244/27.06	01.07
2000	02.05	23.05	28.08	30.06	119	39	3662	2525	170/28.05	30.05	238/22.06	24.06
2001	14.05	30.05	15.08	15.07	94	47	4840	3782	185/08.06	09.06	314/06.07	08.07
2002	06.05	21.05	11.09	02.07	129	43	4330	3355	272/06.06	29.05	225/21.06	25.06
2003	13.05	29.05	24.08	07.07	104	40	5018	3840	199/03.06	04.06	527/24.06	25.06
2004	04.05	01.06	17.08	17.07	106	48	5494	4178	222/03.06	07.06	249/08.07	06.07
2005	23.05	03.06	06.09	13.07	107	41	5201	4132	326/04.06	04.06	240/29.06	02.07
average	12.05	30.05	28.08	05.07	110.2	40.6	4631.7	3518.1	04.06	04.06	29.06	29.06
2007	5.05	30.05	30.07	28.06	87	29	5806	3941	265/08.06	04.06	259/23.06	22.06

[a] SPI—seasonal total pollen counts in the Poaceae atmospheric pollen season; SPI*—seasonal total pollen counts in the estimated Poaceae pollen season; max I—the value and the date of maximum in the phase I of the atmospheric pollen season; max I*—the value and the date of maximum in the phase I of the estimated main pollen season; max II—the value and the date of maximum in the phase II of the atmospheric pollen season; max II*—the value and the date of maximum in the phase II of the estimated main pollen season; length—the duration of the Poaceae atmospheric pollen season; length*—the duration of the estimated Poaceae pollen season; start/start*—the dates (day.month) of the beginning of the Poaceae atmospheric pollen season/the estimated Poaceae pollen season; end/end*—the dates (day.month) of the end of the Poaceae atmospheric pollen season/the estimated Poaceae pollen season.

Table 4 Descriptive statistics of the Poaceae atmospheric pollen seasons and the estimated main pollen seasons (*) in 1995–1996 in Ostrowiec Św[a]

	start	start*	end	end*	length (days)	length* (days)	SPI	SPI*	max I	max I*	max II	max II*
1995	20.05	02.06	04.08	10.07	77	39	5355	4636	356/07.06	06.06	281/01.07	01.07
1996	21.05	31.05	01.09	09.07	113	43	3010	2269	68/07.06	07.06	308/07.07	03.07

[a] SPI—seasonal total pollen counts in the Poaceae atmospheric pollen season; SPI*—seasonal total pollen counts in the estimated Poaceae pollen season; max I—the value and the date of maximum in the phase I of the atmospheric pollen season; max I*—the value and the date of maximum in the phase I of the estimated main pollen season; max II—the value and the date of maximum in the phase II of the atmospheric pollen season; max II*—the value and the date of maximum in the phase II of the estimated main pollen season; length—duration of the Poaceae atmospheric pollen season; length*—duration of the estimated Poaceae pollen season; start/start*—the dates (day.month) of the beginning of the Poaceae atmospheric pollen season/the estimated Poaceae pollen season; end/end*—the dates (day.month) of the end of the Poaceae atmospheric pollen season/the estimated Poaceae pollen season.

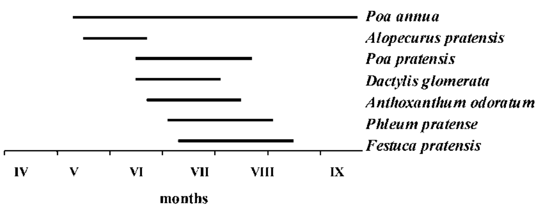

Fig. 4 The periods of maximum flowering among selected grass species in Rzeszów, for years 2003–2004.

Table 5 The dates (day.month) and/day from 1st January of the three hay cuts in the village of Krasne in the years 1997–2005

	I	II	III
1997	05.06/156	30.07/211	07.10/280
1998	04.06/155	23.07/204	16.10/289
1999	07.06/158	27.07/208	13.09/256
2000	30.05/151	26.07/207	20.09/263
2001	28.05/148	27.07/208	17.09/260
2002	28.05/148	23.07/204	16.09/259
2003	29.05/149	09.09/252	
2004	31.05/152	04.08/216	04.10/277
2005	06.06/157	28.07/209	07.10/280
2007	06.06/157	21.09/265	

Results of statistical analysis (Table 6) are in accordance with those which were obtained by the method presented above. The null hypothesis concerning a lack of correlation between pollen counts and weather parameters was rejected. Maximum and mean temperatures, sunshine and relative air humidity had the most effect on daily average pollen counts for all the distinguished periods. Relative air humidity and maximum temperature were the strongest factors, in comparison to the other variables which influenced daily pollen concentrations in the post-peak periods of phases I, II and in the period of lower concentrations between phases I and II (Table 6).

Using multiple regression, three models for forecasting onset of the main pollen season were presented. Only one or two variables were used as independent variables. All the regression coefficients of functions were statistically significant but the models showed a low percentage of variability, especially for phase I (Table 7).

Maximum and mean temperatures were the primary factors that determined the onset of phase I (SPS I*) and phase II (SPS II*), t_1 and t_2. The correlations were negative (Table 8). No significant relationship between these dates and rainfall was stated. In t_1, the linear regression formula explained the highest variability—about 70%. Temperatures of the second and third ten days in April were the best independent variables. For these

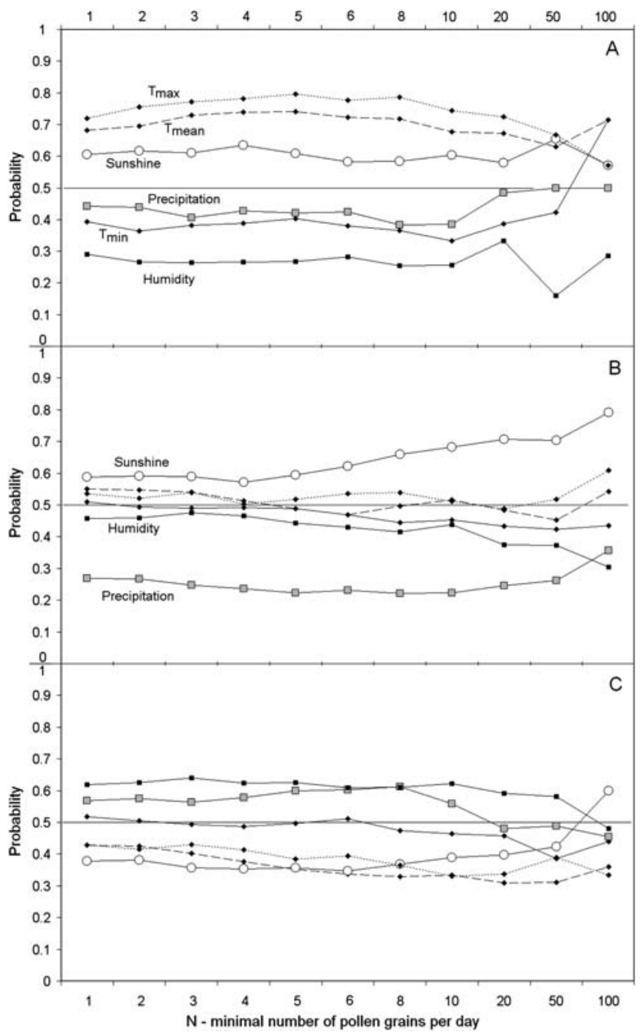

Fig. 5 Probability of the occurrence of days when airborne pollen counts and the values of the meteorological parameters increased simultaneously over two consecutive days (A), the same with one day lag (B) and two days of lag (C).

models, forecast errors were small: ±1 day or no error was noted. In the case of SPS I*, the most important variables were mean and maximum temperatures of the third ten days in April and the first ten days of May. The models explained over 60% of variables. Forecast errors ranged from 0 to 6 days. For SPS II* and t_2, errors were higher, up to 9 days. In 2007, the dates of the main pollen season were observed earlier than in comparison to those which were predicted (Table 9).

Discussion

The above analysis confirmed that in Rzeszów, the patterns of the grass pollen seasons were quite similar to one another in each year. Similar patterns were noted in Ostrowiec Św. (SE Poland) and in Gdańsk (N Poland), although the pollen seasons start a bit later there.[52] In other Polish cities the atmospheric pollen seasons generally had a different character; either one clear maximum was noted, or the pollen seasons were more dispersed.[10,23] Norris-Hill[5] found that in London the grass pollen season was double-peaked, thus it was similar in character to that of Rzeszów. The diagram representing average daily pollen concentrations in Porto, Portugal is also characterised by two peaks.[11] In Basel, Switzerland the main grass season generally occurred in the first half of June but in some years second peaks were noted.[53] Pollen season dates determined by the percentage method and those calculated from the formula used by the authors differ considerably, but on average, three-quarters of all pollen grains recorded by the former method occurred in the period determined by this formula. This technique eliminates the long tails of low values at the onset and end of the Poaceae pollen season. Therefore, the period determined by this formula can be considered to consist of the main grass pollen season. It was confirmed by high R^2 values observed in the year 2007 and data from Ostrowiec Św. This algorithm is universal. It can be used to described bimodal main pollen seasons of different taxa in different bioclimatic regions. The authors suggest using it to define the main Poaceae pollen seasons elsewhere in Europe: for example in Málaga, Spain[6] as well as Porto, Portugal.[11]

Similar to other European countries, the most important parameters affecting variation in daily pollen concentrations in Poland are the temperature, in particular the maximum temperature, sunshine and relative air humidity.[12,22,23,34,36,37] It has been shown with great probability that on days in which the maximum temperature, mean temperature and sunshine rise, an increase in grass pollen concentrations are noted, and in the case of air humidity, the concentration decreases. Weather influenced daily grass pollen concentrations the following day. The most important factors were precipitation and sunshine. Rainfall affects pollen concentrations in different ways. At the onset of rainfall, pollen grain counts increase for a short time. Later, pollen is washed out of the air.[54]

An important question arises here whether the meteorological parameters really influence the decrease noted in pollen counts which occurred at about the middle of June, between the two phases. At this time in Europe, including Poland, a certain weather pattern is formed, colloquially called the European monsoon. This phenomena brings rainfall, increased relative air humidity and reduced temperatures,[46,55] thus producing factors which as shown earlier decrease pollen counts. This analysis does not give a clear answer whether the monsoon or other factors are the cause of this decrease. During the time of observation, the daily average pollen counts depended on maximum temperature (positive correlation) and relatively humidity (negative correlation), but a similar correlation was found for the post-peak periods of the phases I, II.

Knowledge of the flowering phenology of each species may help in interpreting the curves representing patterns of pollen seasons.[42,44,45] It can be assumed that grass species, which are common among the local flora, are the main source of airborne pollen.[18] The phenological observations of common grass species indicate that those with abundant pollen production begin flowering in a relevant order; the earliest beginning to flower is *Alopecurus pratensis* (meadow foxtail), and when the full pollination period for this species ends, the next species with abundant pollen production has started flowering, such as *Dactylis glomerata* (orchard grass) and *Festuca pratensis* (meadow fescue). The flowering periods of others species overlapped,

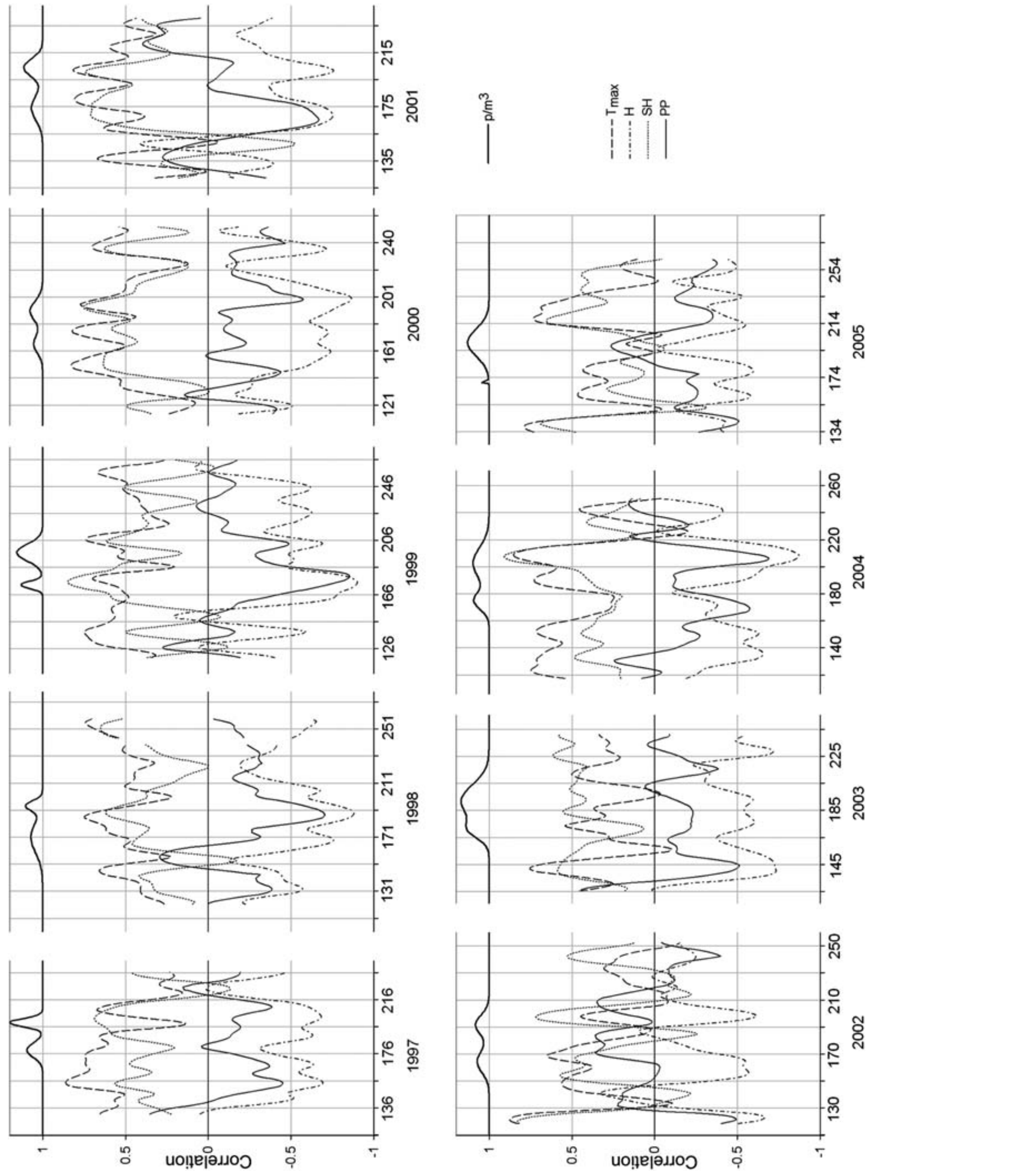

Fig. 6 The 5-day Gaussian-weighted moving correlation coefficients between Poaceae daily pollen counts and selected meteorological parameters in Rzeszów, for years 1997–2005. Days from 1st January are numbered for each year. (p/m^3—pollen grain per m^3; T_{max}—maximum temperature; H—relative air humidity; SH—sunshine; PP—precipitation).

constituting the long atmospheric pollen season.[26] Norris-Hill[34] claimed that the bimodal distribution of the grass pollen season results in different flowering periods for each grass species. This order in the sequence of pollen release seems to correspond to this characteristic curve in the atmospheric pollen season. The environs of Rzeszów are a mosaic of forests and crop fields; agricultural land occupies a greater part of the land-use structure. Many aerobiological monitoring stations are located in urbanised areas and industrialised regions. This may partially explain why grass pollen seasons are quite different between many European regions.[7,8,12,53]

In Poland, depending on what yield a farmer wishes to have, and of what quality, from two to three or even four hay cuts are taken. The most important grasses of the hay meadows include: meadow foxtail, orchard grass, timothy grass, and meadow fescue. Typical pastures include: bluegrass, red fescue, and rye grass. The meadows are first cut between late May to early June. A higher quality harvest is thereby obtained.

Table 6 Spearman correlation coefficients between the numbers of pollen grains recorded in Rzeszów in the years 1997–2005 and selected meteorological factors[a]

	T_{max}	T_{min}	T_{mean}	PP	H	SH	WS
all the main pollen seasons	0.53	NS	0.46	−0.31	−0.40	0.40	−0.12
the phases I	0.45	0.19	0.45	−0.23	−0.32	0.31	−0.11
the phases II	0.60	NS	0.52	−0.30	−0.34	0.39	−0.21
the periods of low concentrations between the phases I, II	0.47	NS	0.36	−0.34	−0.57	0.46	−0.02
the pre-peak periods of the phases I,II	0.53	0.19	0.50	−0.29	−0.20	0.26	NS
the post-peak periods of the phases I,II	0.58	NS	0.53	−0.20	−0.42	0.45	−0.24

[a] T_{max}—maximum temperature; T_{min}—minimum temperature; T_{mean}—mean temperature; PP—precipitation; H—relative air humidity (%); SH—sunshine; WS—wind speed, NS—not statistically significant; $\alpha \leq 0.05$.

Table 7 The results of multiple regression analysis for average daily pollen counts (square root) and significant meteorological parameters[a]

Period	Regression function	R^2
the phase I	$y = (15.5 - 0.1*H)^2$	0.11
the phase II	$y = (3.3 + 0.65*T_{max} - 0.22*T_{min})^2$	0.36
the period of low concentrations between the phases I, II	$y = (8.6 + 0.20*T_{max} - 0.1*H)^2$	0.42

[a] T_{max}—maximum temperature; H—relative air humidity (%); R^2—determination coefficient.

Table 8 Significant Pearson correlation coefficients between the dates of the main Poaceae pollen season recorded in Rzeszów in the years 1997–2005 and selected meteorological factors[a]

	Independent variables		
	Temperature	Period	r
SPS I*	T_{mean}	2,3 April	−0.7153
		3 April	−0.7035
		3 April, 1 May	−0.8146
	T_{max}	2,3 April	−0.7347
		3 April	−0.6936
		3 April, 1 May	−0.8358
		1 May	−0.7707
SPS II*	T_{mean}	2,3 April	−0.7192
		3 April	−0.6739
	T_{max}	2,3 April	−0.7423
		3 April	−0.6899
		3 April, 1 May	−0.6605
t_1	T_{mean}	2 April	−0.8513
		2,3 April	−0.8379
	T_{max}	2,3 April	−0.8357
t_2	T_{mean}	3 April	−0.6803

[a] SPS I*—start of the phase I of the main pollen season; SPS II*—start of the phase II of the main pollen season; r—the Pearson correlation coefficient; T_{max}—maximum temperature, T_{mean}—mean temperature; Arabic numerals indicate which day period of a particular month; $\alpha < 0.05$.

Land use determines the pollen spectrum. Airborne Poaceae pollen grains are mainly associated with mowing.[56,57] The province of Rzeszów has an agricultural character. The meadows and pastures in close proximity to the aerobiological stations are the main source of grass pollen.[24] The species flowering earliest, such as annual bluegrass and meadow foxtail, probably released pollen in the first phase of the pollen season. The first hay cut was taken during this time, and from several to a dozen or so days later, a decrease in airborne grass pollen counts was noted. This time lag could result from the short time increase of pollen grain counts during or just after hay cutting. This phenomena was observed during harvesting.[17] It is also possible that other nearby meadows were cut at a different time.

Since 2005 an increasing number of farms have joined the agri-environmental package of the European Union (EU), and in accordance with single-market laws, the frequency of meadow cutting is changed. According to the EU regulations, the meadows can be cut for the first time after 1st July. If this programme involves the majority of agricultural farms, it will be possible to assess whether the hay cutting dates really do have an effect on the decline in the pollen concentration in the middle of June, or whether the seasonality of grass flowering is the actual cause. In Spanish Galicia, a change in land use affected the Poaceae pollen season and overall pollen counts.[24] Analyses of the data heretofore show that it is actually the sequence of flowering grass species and resulting hay cutting dates which seem to cause the characteristic grass pollen season observed in Rzeszów.

Analyses show that it is possible to predict the start and peak dates of the main grass pollen season after taking meteorological variables into account, but only several parameters were statistically significant in regression formulas. For Poznań (Poland), meteorological variables satisfactory correlated much more with the start of the Poaceae pollen season and peak days. The best models included May temperatures, March rainfall and NAO indices.[21] For Rzeszów however, April temperatures produced the best models. The model for forecasting peak day (t_1) in Rzeszów was more accurate in comparison to those for Poznań,[21] and Spain.[22] In determining SPS I* the model used for Rzeszów was worse than that used for Poznań, but still satisfactory. Garcia-Mozo *et al.*[22] reported great yearly variations in the SPS of a Poaceae pollen season compared with the peak day, because early-flowering grass species like *Dactylis glomerata* (orchard grass), are more responsive to weather. In Rzeszów, most grass species flower during the second phase of the main pollen season, which probably resulted in the greater error in forecasting SPS II* and the second peak day.

Table 9 The linear regression models for selected meteorological variables and starts of the phases I and II (SPS I*, SPS II*), dates of maximum pollen counts in the phase I and phase II (t_1, t_2) and forecasting errors for 2007 year[a]

	Linear regression functions	R^2 (%)	Observed *vs.* expected for 2007 (in days)
SPS I*	$y = (-1.3012*1\text{May } T_{max}) + 177.3$	59.4	−6
	$y = (-1.2071*3\text{April } T_{max}) + 170.33$	48.1	0
	$y = (-1.5319*3\text{April } T_{mean}) + 166.82$	49.5	−1
	$y = (-2.2189*3\text{April,1May } T_{mean}) + 177.6$	66.3	−5
	$y = (-1.634*3\text{April,1May } T_{max}) + 108.9$	69.8	−4
	$y = (-1.238*2,3\text{April } T_{max}) + 169.26$	53.9	−1
	$y = (-1.5045*2,3\text{April } T_{mean}) + 164.76$	51.1	0
SPS II*	$y = (-1.4679*3\text{April } T_{max}) + 197.61$	47.6	−5
	$y = (-1.5788*3\text{April,1May } T_{max}) + 202.75$	48.6	−9
	$y = (-1.5292*2,3\text{April } T_{max}) + 196.68$	55.1	−4
	$y = (-1.7941*3\text{April } T_{mean}) + 192.58$	45.4	−6
	$y = (-1.8496*2,3\text{AprilT}_{mean}) + 191.04$	51.7	−5
t_1	$y = (-1.2935*2,3\text{April } T_{max}) + 176.01$	69.8	1
	$y = (-1.619*2,3\text{April } T_{mean}) + 170.77$	70.2	0
	$y = (-1.3248*2\text{April } T_{mean}) + 167.34$	72.4	+1
t_2	$y = (-1.4539*3\text{April } T_{mean}) + 197.4$	46.2	−9

[a] Arabic numerals indicate which day period of a particular month; R^2—determination coefficient; predicted year (2007) was not included into models.

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References

1 W. D. Clayton, *Ann. Missouri Bot. Gard.*, 1981, **68**, 5–14.
2 B. Tokarska-Guzik, in *Problems of grass biology*, ed. L. Frey, Szafer Institute of Botany, Polish Academy of Sciences, Kraków, 2003, pp. 125–140.
3 G. D'Amato, L. Cecchi, S. Bonini, C. Nunes, I. Annesi-Maesano, H. Behrendt, G. Liccardi, T. Popov and P. van Cauwenberge, *Allergy*, 2007, **62**, 976–990.
4 B. Erbas, J. H. Chang, S. Dharmage, E. K. Ongw, R. Hyndmanz, E. Newbigin and M. Abramsonz, *Clin. Exp. Allergy*, 2007, **37**, 1641–1647.
5 J. Norris-Hill, *Aerobiologia*, 1997, **13**, 91–97.
6 D. Fernéndez-González, R. M. Valencia-Barrera, A. Vega, C. Díaz de la Guardia, M. M. Trigo, A. Guárdia, C. Pertińez and F. J. Rodríguez Rajo, *Polen*, 1999, **10**, 127–136.
7 J. A. Sánchez Mesa, M. Smith, J. Emberlin, U. Allitt, E. Caulton and C. Galán, *Aerobiologia*, 2003, **19**, 243–250.
8 F. Latorre and J. Belmonte, *Grana*, 2004, **43**, 156–163.
9 M. Smith, J. Emberlin and A. Kress, *Aerobiologia*, 2005, **21**, 85–94.
10 K. Chłopek, *Acta Agrobot.*, 2007, **60**(2), 79–86.
11 I. Abreu, N. Ribeiro, H. Ribeiro, M. Oliviera and A. Cruz, *Aerobiologia*, 2008, **24**, 133–140.
12 R. Peternel, L. Smec, J. Ulig, I. Hrga and P. Hercog, *Grana*, 2006, **45**(2), 130–136.
13 I. J. Smart, W. G. Tuddenham and R. B. Knox, *Aust. J. Bot.*, 1979, **27**, 333–342.
14 J. C. Prieto-Baena, P. J. Hidalgo, E. Domínguez and C. Galán, *Grana*, 2003, **42**, 153–160.
15 C. S. Reddi and N. S. Reddi, *Grana*, 1986, **25**, 55–61.
16 N. Aboulaich, H. Bouziane, M. Kadiri, M. Trigo, H. Riadi, M. Kazzaz and A. Merzouki, *Aerobiologia*, 2009, **25**, 27–38.
17 V. A. Hall, *Pollen et Spores*, 1988, **2**, 265–270.
18 J. A. Sánchez Mesa, C. Galán and C. Hervás, *Int. J. Biometeorol.*, 2005, **49**, 355–362.
19 P. Comtois and D. Sherknies, *Grana*, 1991, **30**, 184–189.
20 C. S. Reddi, N. S. Reddi and B. Atluri Janaki, *Rev. Paleobot. Palynol.*, 1988, **54**, 11–42.
21 A. Stach, M. Smith, J. C. Prieto-Beana and J. Emberlin, *Environ. Exp. Bot.*, 2008, **62**, 323–332.
22 H. García-Mozo, C. Galán, J. Belmonte, D. Bermejo, P. Candau, C. Díaz de la Guardia, B. Elvira, M. Gutiérrez, V. Jato, I. Silva, M. M. Trigo, R. Valencia and I. Chuine, *Agric. Forest Meteorol.*, 2009, **149**, 256–262.
23 M. Puc and M. I. Puc, *Ann. Agric. Environ. Med.*, 2004, **11**, 237–244.
24 V. Jato, F. J. Rodríguez-Rajo, M. C. Seijo and M. J. Aira, *Int. J. Biometeorol.*, 2009, **53**, 333–344.
25 M. Laaidi, *Int. J. Biometeorol.*, 2001, **45**, 1–7.
26 R. L. Edmonds, *Aerobiologia. The Ecological systems approach.* Dowden, Hutchinson & Ross, Inc. Stroudsburg, Pennsylvania, 1979.
27 E. Pacini, *Plant Syst. Evol.*, 2000, **222**, 19–43.
28 B. J. Green, M. Dettmann, E. Yli-Panula, S. Rutherford and R. Simpson, *Int. J. Biometeorol.*, 2004, **48**, 172–178.
29 A. S. N. Liem, *Grana*, 1980, **19**, 21–29.
30 R. G. Flood and G. M. Halloran, *Ann. Bot.*, 1982, **49**, 469–475.
31 A. S. N. Liem, *Rev. Palaeobot. Palynol.*, 1973, **15**, 3–16.
32 P. E. Taylor, R. C. Flagan, R. Valenta and M. M. Glovsky, *J. Allergy Clin. Immunol.*, 2002, **109**, 51–56.
33 I. S. Palacios, R. T. Molinia and A. F. M. Rogríguez, *Aerobiologia*, 2007, **23**, 17–26.
34 J. Norris-Hill, *Grana*, 1995, **34**, 182–188.
35 F. Th. Spieksma, J. M. Corden, M. Detandt, W. M. Millington, H. Nikkels, N. Nolard, C. H. H. Schoenmakers, L. A. de Weger, R. Willems and J. Emberlin, *Aerobiologia*, 2003, **19**, 171–184.
36 H. Ribeiro, M. Cuncha and I. Abreu, *Aerobiologia*, 2003, **19**, 21–27.
37 R. M. Valencia-Barrera, P. Comtois and D. Fernández-González, *Grana*, 2001, **40**, 223–229.
38 M. Smith, J. Emberlin, A. Stach, A. Rantio-Lechtimäki, E. Caulton, M. Thibaudon, Ch. Sindt, S. Jäger, R. Gehring, G. Frenguelli, V. Jato, F. J. Rodriguez-Rajo, P. Alcázar and C. Galán, *Aerobiologia*, 2009, 10.1007/s10453-009-9136-4.
39 R. Zerboni, P. V. Arrigoni, M. Manfredi, M. Rizzotto, L. Paoletti and C. Ricceri, *Grana*, 1991, **30**, 357–363.
40 S. Hicks, *Aerobiologia*, 1992, **8**, 220–230.
41 H. García Mozo, E. Dominguez-Vilches and C. Galán, *Ann. Agric. Environ. Med.*, 2007, **14**, 63–69.
42 A. L. Zanotti and G. Puppi, *Aerobiologia*, 2000, **16**, 199–206.
43 N. Estrella, A. Menzel, U. Krämer and H. Behrendt, *Int. J. Biometeorol.*, 2006, **51**, 49–59.
44 V. Jato, F. J. Rodríguez-Rajo and M. Aira, *Aerobiologia*, 2007, **23**, 91–105.
45 V. Jato, F. J. Rodríguez-Rajo and M. Aira, *Ann. Agric. Environ. Med.*, 2007b, **14**, 271–280.
46 A. Woś, *Klimat Polski. Wyd. Nauk. PWN, Warszawa*, 1999, 207–209 (The climate of Poland).

47 T. Niedźwiedź, *Sytuacje synoptyczne i ich wpływ na zróżnicowanie przestrzenne wybranych elementów klimatu w dorzeczu górnej Wisły*. Rozprawy Habilitacyjne nr 58. Uniwersytet Jagielloński, Kraków, 1981. (*Synoptic situations and their influence on spatial differentiation of chosen elements of climate of the upper Wisła Basin*).
48 *Podkarpacie Statistical Office* 2002.
49 *Świętokrzyskie Statistical Office* 2002.
50 A. Łukaszewicz, *Wiad. Bot.*, 1984, **28**(2), 153–158.
51 F. Święs, *Roślinność synantropijna miasta Rzeszow*. Wyd. Uniw. Marii Curie-Skłodowska, Lublin, 1993. (*The synanthropic vegetation of the city of Rzeszów*).
52 M. Latałowa, A. Uruska, A. Pędziszewska, M. Góra and A. Dawidowska, *Grana*, 2005, **44**, 192–201.
53 R. M. Leuschner, H. Christen, P. Jordan and R. Vonthein, *Aerobiologia*, 2000, **16**, 381–391.
54 J. Norris-Hill and J. Emberlin, *Aerobiologia*, 1993, **9**, 27–32.
55 K. Fortuniak, K. Kożuchowski and E. Żmudzka, *Prz. Geof.*, 2001, **XLVI**(4), 283–303.
56 M. J. Gaillard, H. J. B. Birks, U. Emanuelsson, S. Karlsson, P. Laderĺs and D. Olausson, *Rev. Paleobot. Palynol.*, 1994, **82**, 47–73.
57 J. Emberlin, M. Savage and S. Jones, *Clin. Exp. Allergy*, 1993, **23**, 911–918.