



Unusually high birch (*Betula* spp.) pollen concentrations in Poland in 2016 related to long-range transport (LRT) and the regional pollen occurrence

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Abstract In 2016, the highest birch (*Betula* spp.) pollen concentrations were recorded in Kraków (Poland) since the beginning of pollen observations in 1991. The aim of this study was to ascertain the reason for this phenomenon, taking the local sources of pollen in Poland and long-range transport (LRT)

episodes associated with the pollen influx from other European countries into account. Three periods of higher pollen concentrations in Kraków in 2016 were investigated with the use of pollen data, phenological data, meteorological data and the HYSPLIT numerical model to calculate trajectories up to 4 days back

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(96 h) at the selected Polish sites. From 5 to 8 April, the birch pollen concentrations increased in Kraków up to 4000 Pollen/m³, although no full flowering of birch trees in the city was observed. The synoptic situation with air masses advection from the South as well as backward trajectories and the general birch pollen occurrence in Europe confirm that pollen was transported mainly from Serbia, Hungary, Austria, the Czech Republic, Slovakia, into Poland. The second analyzed period (13–14 April) was related largely to

the local flowering of birches, while the third one in May (6–7 May) mostly resulted from the birch pollen transport from Fennoscandia and the Baltic countries. Unusual high pollen concentrations at the beginning of the pollen season can augment the symptomatic burden of birch pollen allergy sufferers and should be considered during therapy. Such incidents also affect the estimation of pollen seasons timing and severity.

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et al. 2008; Skj  th et al. 2007; Szczepanek et al. 2017), (ii) grass pollen (Smith et al. 2005) and (iii) weed pollen (Kasprzyk et al. 2011; Makra & P  lfi 2007;   koparija et al. 2013; Smith et al. 2008; Stach et al. 2007). Pollen grains of alder (*Alnus* spp.), birch (*Betula* spp.) and the pine family (Pinaceae) are the most frequently transported pollen among trees over long distances (Hjelmroos 1992; Skj  th et al. 2007; Szczepanek et al. 2017). LRT events of birch pollen occur rather rarely and usually outside the predicted pollen season, according to Skj  th et al. (2007) and Puc (2014). However, pollen allergy sufferers are unprotected during the time of unexpected pollen exposure which will therefore have a full allergenic impact (Skj  th et al. 2007). Although pollen is considered to be a local-scale natural pollutant (Sofiev, Siljamo et al. 2006), many reports indicate a potential influence of pollen allergens transported in large amounts over greater distances on the health condition of patients (Cecchi et al. 2006, 2010; de Weger et al. 2016; Hjelmroos 1992; Skj  th et al. 2007, 2009; Veriankait   et al. 2010). In addition, a recent study on Amb a 1 allergen measurements in Pozna   shows that ragweed pollen grains can cause allergic reactions not only in heavily infested areas, but also in unaffected regions due to LRT events (Grewling et al. 2016).

Cecchi et al. (2010), analyzing the increase in new incidences in ragweed allergy in Italy, concluded that the impact of the transported pollen should be considered as exacerbating the allergic symptoms, not as a factor provoking the new sensitizations. This can be explained by the fact that LDT episodes do not occur every pollen season, and pollen allergenicity is weakened during the pollen travel in the higher layer of the atmosphere, where it is subjected to extreme air temperature, humidity and solar radiation.

To confirm the impact of LRT on the intensely higher pollen concentrations (episodes), a back trajectory analysis of air masses can be performed (Kasprzyk et al. 2011; Skj  th et al. 2007). The track of LRT events of pollen can be traced before the regular pollen season, if phenological observations are performed simultaneously (Mahura et al. 2007; Ranta et al. 2007; Robichaud & Comtois 2017; Skj  th et al. 2007).

Sometimes, it is difficult to establish an adequate relationship between the source of the pollen grains and the site of pollen deposition due to the complicated large-scale dispersion patterns affecting pollen

transport. Therefore, the most evident impact of LRT on pollen occurrence in a given region is the detection of exotic pollen grains, considered as “foreign” (not locally produced) pollen (Cabezudo et al. 1997; Kasprzyk et al. 2011; Rousseau et al. 2008; Smith et al. 2008).

The reason for the current study was an unusually high daily birch pollen concentration (> 4000 Pollen/ m^3) in Krak  w in 2016, never observed since the start of regular volumetric pollen measurements in 1991. High birch pollen concentrations were also observed in the southern and central parts of Poland before the flowering of the local birches. During this time, patients suffering from birch pollen allergy experienced intense allergy symptoms such as: runny nose, conjunctivitis as well as asthmatic dyspnea symptoms (personal communication, Centre of Clinical and Environmental Allergology, University Hospital, Krak  w). Therefore, the purpose of this work was to analyze the birch pollen season in 2016 in Krak  w in detail against a background of the phenological observations, in relation to the local sources of the pollen release in Poland and LRT episodes from other European countries.

2 Materials and methods

An unusual high daily birch pollen concentration (> 4000 Pollen/ m^3) in Krak  w (Southern Poland) (50  04'N, 19  58'E, 220 m a.s.l.) at the beginning of April 2016 was taken as the “starting point” for the assessment of the potential inflow of pollen from outside of the local sources. In 2016, simultaneously with the pollen sampling, the phenological observations of *Betula pendula* specimen were conducted from 1 March to 1 May. Data were obtained at 12 sites in Krak  w, selected in a 5-km range from the aerobiological monitoring station. After   ukasiewicz (1984), seven phenological phases were distinguished: F1—the appearance of the first flower buds, F2—first blooming flowers, F3—beginning of full flowering (25% open flowers), F4—appearance of the first withered flowers, F5—end of full flowering (75% withered flowers), F6—last blooming flowers and F7—end of blooming. Observations were carried out at intervals lasting 2–3 days. In order to determine the phenological phase, inflorescences of 3 selected

individuals were examined at each site. The mean phenological phases for Kraków were determined.

The birch pollen season in 2016 was presented against a background of a long data series encompassing the years 1991–2018 in Kraków, where pollen monitoring was performed using the volumetric method with Hirst type samplers (Hirst 1952) according to the standard recommendations of the European Aerobiology Society (Galán et al. 2014).

Birch pollen season characteristics (the season start, end, duration and Seasonal Pollen Integral, SPIn) were calculated using the 95% method, i.e., the season beginning was calculated as 2.5% of the annual pollen sum (Annual Pollen Integral, APIn) and the season end as 97.5% of the annual total (Kasprzyk et al. 2015). The Seasonal Pollen Integral (SPIn) (Galán et al. 2017) was calculated by summing up the daily mean birch pollen concentrations throughout a given season. Descriptive statistics (mean, SD, CI, V%) were used to estimate the variability of seasonal dynamics. Moreover, the distribution of the daily pollen concentrations in all study years was estimated to detect their potential increases at the very beginning of the season and the secondary maximum values at the season end.

The identified episodes of increased daily pollen concentrations in 2016 were analyzed considering the possibility of the pollen distant transport. For this purpose, pollen concentrations at the pollen monitoring sites in Poland and in other European countries (Austria, the Czech Republic, Finland, Lithuania, Slovakia, Slovenia, Serbia, Switzerland, and Sweden) selected for the study were studied (Fig. 1).

Daily birch pollen concentrations at the selected sites as well as meteorological conditions in synoptic stations localized near aerobiological stations were compared, including wind direction and speed, direction of air masses, advection and backward trajectories. Therefore, maps of the synoptic situation and meteorological data from the Institute of Meteorology and Water Management–National Research Institute (IMWM-NRI) (www.pogodynka.pl) and the German meteorological service–Deutscher Wetterdienst Offenbach (DWD) (www1.wetter3.de) were used. The Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) was used to analyze the backward trajectories. This system was created by the NOAA (Air Resources Laboratory; <http://www.arl.noaa.gov>; Stein et al. 2015). The online version was used. The data (with a spatial resolution 1×1 degree;

GDAS1) used to calculate the backward trajectories come from the GDAS operational systems (Global Data Assimilation System; <http://www.arl.noaa.gov>), which are often used to study the movement of the air masses. Backward trajectories were used up to 4 days back (96 h) at 500 m (the transitional level, where the air flow is strongly modified by varying topography) and 1000 m (the free atmosphere, where the effect of the earth surface friction is disappearing) above ground level (a.g.l.). For the sake of clarity of the figures, limiting the presentation to the 12 o'clock trajectory was decided. Trajectories for other hours during the day were checked, and those from 12.00 turned out to be representative. More details regarding the HYSPLIT numerical model can be found in Fernández-Rodríguez et al. (2014, 2015), Hernández-Ceballos et al. (2014), Jochner et al. (2015) and Szczepanek et al. (2017).

Maps including birch pollen concentrations were produced in ArcGIS Software. Data were drawn for the days by applying the radial basis functions (RBF) method. This is an exact interpolation technique, which takes the general tendencies and the local variability into account.

In order to characterize the weather conditions in Kraków from March to May, the following measurements were also used: air temperature (°C), relative humidity (%), precipitation (mm), sunshine duration (hours) and cloudiness (%). The spatial distribution of dust concentration near the ground was taken from the National and Kapodistrian University of Athens (<https://forecast.uoa.gr/en/forecast-maps/dust/europe>).

3 Results

The birch pollen season dynamics in 2016 in Kraków indicate three events of high birch pollen concentrations (Fig. 2). The first period was observed between 5 and 8 April when the daily pollen concentration reached 4199 Pollen/m³ (on 6 April). The second episode was detected about two weeks later during 13–14 April, whereas the third episode was recorded from 6 to 7 May.

The first flowering specimens of *B. pendula* were found on 30 March, but the majority of the trees (more than 90%) started flowering on 2 April (start of mean F2 phase). While most of the birches end blooming on

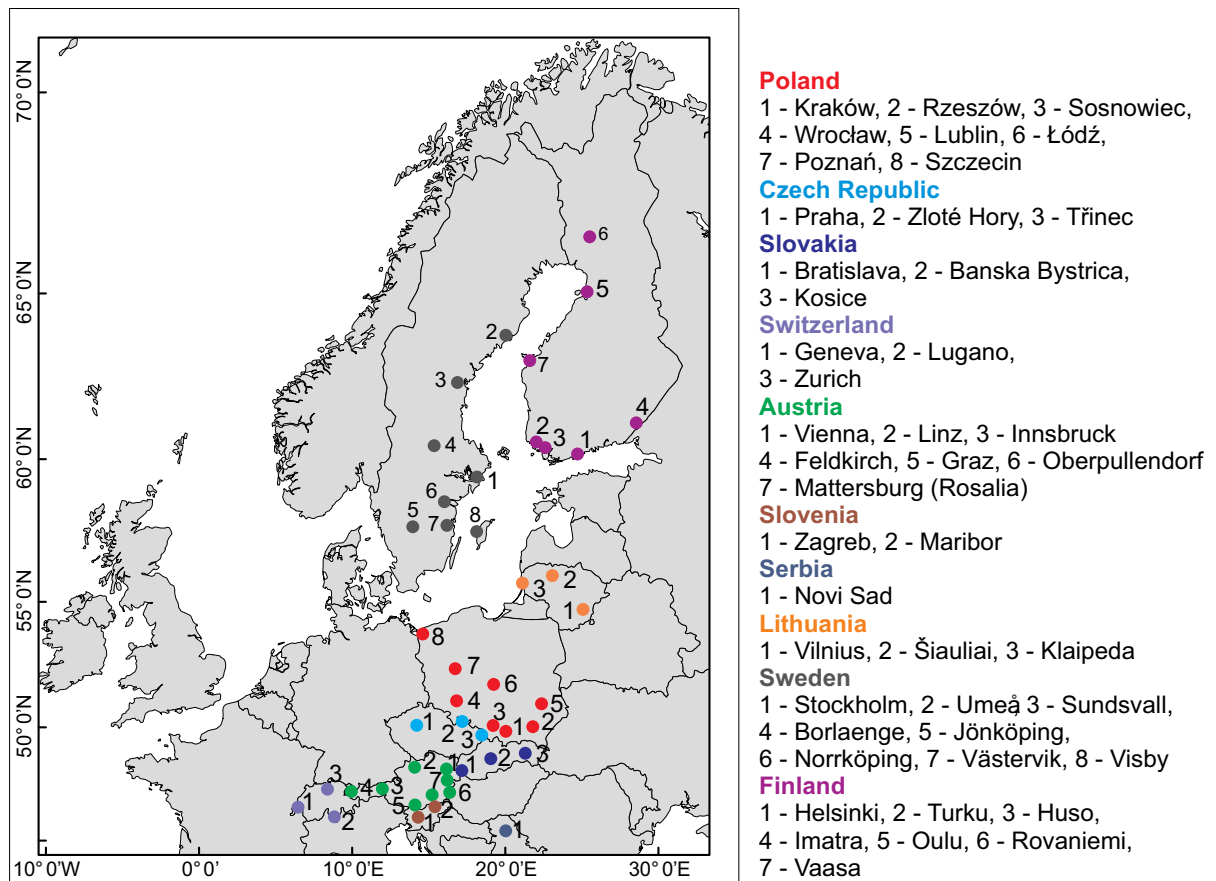


Fig. 1 Location of pollen monitoring sites employed in the study

19 April (start of mean F7 phase), the last flowering specimen was recorded on 26 April. The mean flowering season lasted 17 days and covered the entire pollen season calculated using the 95% method (Fig. 2). The evaluation of the birch SPI_n of the last 28 years (1991–2018) in Kraków revealed that in 2016 the birch pollen concentrations were the highest in the studied period and estimated as an outlier value (Table 1, Fig. 3). The birch pollen seasons at the studied sites in Poland (especially in the southern part of the country) are the background for the detailed analyses of the three discussed episodes (Fig. 4).

The first episode showed a gradual, although intense and rapid increase in pollen concentrations in Kraków (Figs. 2, 4). The phenological observations from 3 to 8 April indicated that only phenological phases 2 and 3 (blooming of the first flowers and 25% of flowers open) were achieved by most of the birch trees (Fig. 2). From April 3 to 5, 2016, areas of high air pressure with the center on the Black Sea influenced

Southern and Eastern Europe (Fig. 5a). In the western and northern parts of the continent, low-pressure centers moved with the system of atmospheric fronts from the Atlantic (synoptic maps: www.pogodynka.pl and www.1.wetter3.de). This air pressure distribution caused an influx of air masses from the Sahara desert to Southern and Central Europe, which could be confirmed by the course of backward trajectories (Fig. 5b), and a thick layer of particulate matter in the air, including sand from the Sahara desert, was also observed by various weather services (including the Polish meteorological office – IMWM-NRI) (Fig. 5c). The tropical air masses, dust and sand, including pollen grains of anemophilous plants such as birch, coming from Southern and Central European countries reached southern Poland. The spatial distribution of birch pollen was attributed to the sources of origin mainly from the Balkan Peninsula, Romania, Hungary and Slovakia with transport distances over 600 km (Fig. 5d).

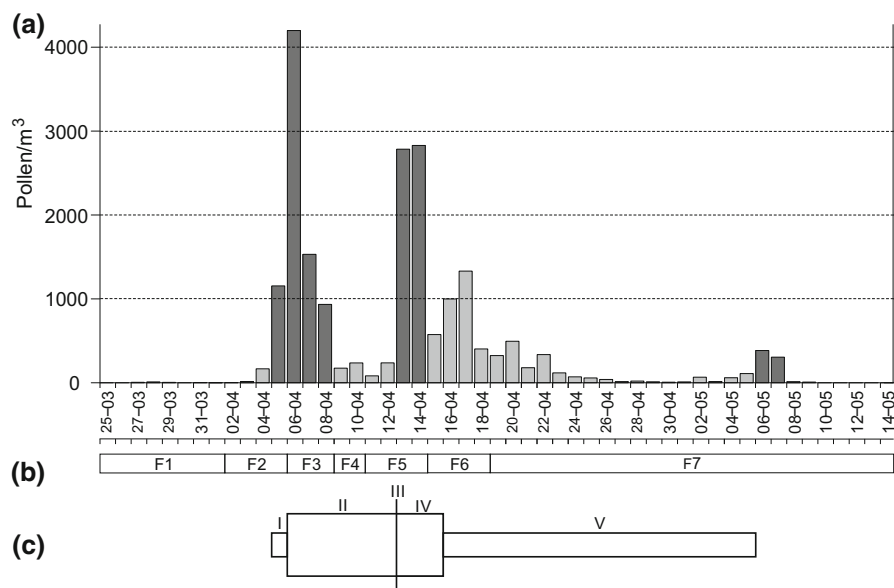


Fig. 2 Daily birch pollen concentrations in Kraków, in 2016 (a); mean phenological phases acc. to the Material and methods (b); pollen season calculated by the 95% method presented as

the following intervals: I (2.5%-25.0%), II (25.0%-50%), III (50%), IV (50%-75%), V (75%-97.5%) of APIn, respectively (c)

Table 1 Descriptive statistics of birch season characteristics in Kraków, in 1991–2018

	Season start*	Season end*	Season duration**	SPIn***	Maximum concentration***	Date of max. concentration*
Min	88.00	114.0	15.00	833.00	119.00	93.00
Median	100.00	126.50	25.00	3 147.50	641.00	107.00
Max	114.00	190.00	77.00	19 791.00	4 199.00	123.00
$\bar{x}$	101.18	128.18	28.00	5 078.18	1 020.24	107.71
SD	6.76	13.99	12.66	4 792.02	1 013.47	7.57
V%	6.68	10.91	45.21	94.37	99.34	7.92

*Consecutive day from the 1st of January; ** number of days; *** Seasonal Pollen Integral (Pollen-day/m³)

Min—minimum value; max—maximum value; $\bar{x}$ mean value; SD—Standard Deviation; V%—coefficient of variance (%)

From 7 to 8 April, a change in the distribution of the baric systems over Europe (lows and highs) was recorded, which led to changes in the weather conditions, in Kraków as well (Fig. 6). During the fourth phenological phase (first flowers being withered), a clear decrease in pollen concentration was observed, probably caused by rainfall in the preceding days (7–8 April) (Fig. 6).

Between the first and the second time frames of high birch pollen concentrations, the daily concentrations ranged from 80 to 240 Pollen/m³ (Fig. 2). During this time, Poland was influenced by reduced air

pressure and no advection situation characterized by the presence of weak winds. The analysis of backward trajectories indicated a local pollen source. This was confirmed by phenological observation in Kraków (fourth phenological phase) (Fig. 2).

From 13 to 14 April, the second highest seasonal pollen concentrations were observed in Kraków during phenological phases 5 (75% of flowers withered) and 6 (last flowering flowers), when most of pollen was already released from the anthers. At all the other studied sites in Poland, very high pollen concentrations related to the local pollen season were

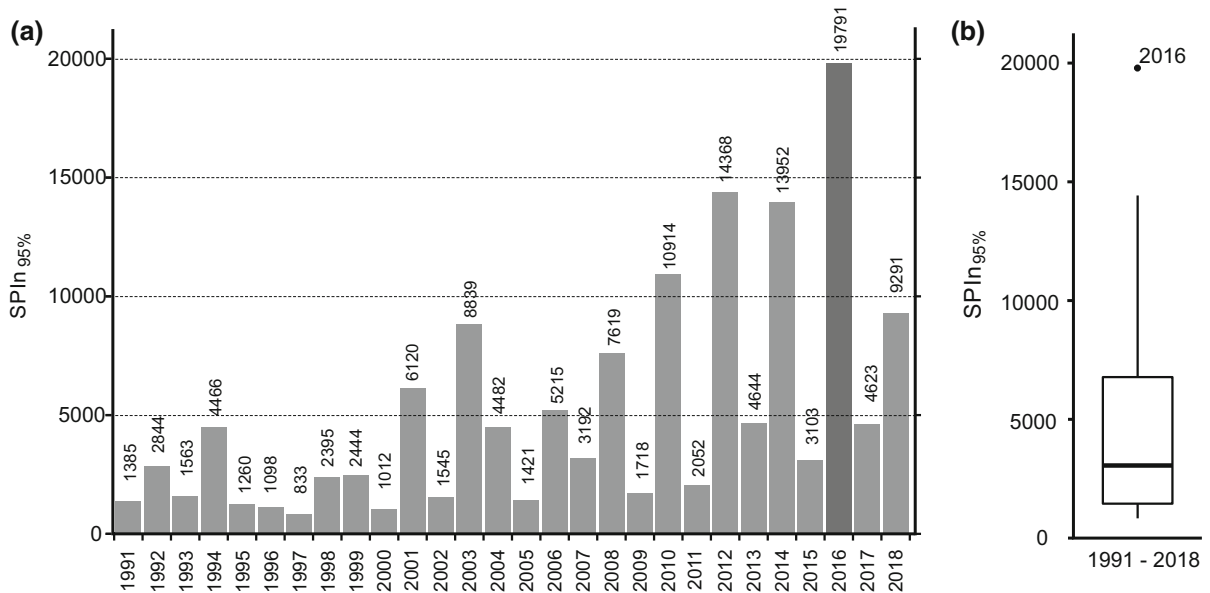


Fig. 3 Seasonal Birch Pollen Integral (SPIn) in Kraków, in 1991–2018 presented as a bar plot (a) and a box plot (b). Box plot indicates 2nd and 3rd quartiles, bold line represents the

median value; the whiskers represent the range after excluding the outliers, which are defined as data points falling outside of the 2nd and 3rd quartiles by more than 1.5-times the IQR

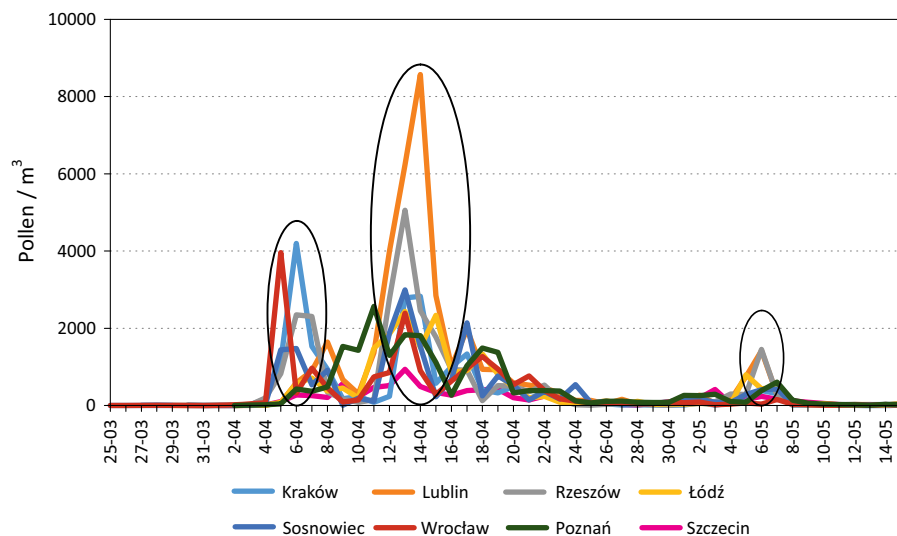


Fig. 4 Daily birch pollen concentrations in selected Polish cities in 2016

observed in similar time, achieving the highest values in Lublin, Rzeszów and Poznań (Figs. 4, 7).

The third episode of high birch pollen concentrations (384 and 395 Pollen/m³, respectively) occurred at the end of the analyzed season (Fig. 2). Such late increases in concentrations appeared in previous seasons, although not always reaching such high values, usually only several pollen grains per day (Szczepanek 1994;

Myszkowska 2013). The analysis of weather conditions indicated that pollen grains derived from the Fennoscandian region, especially from Finland, most probably Russia and the Baltic countries (Lithuania) (Fig. 8), and were transported over a distance up to 1,400 km to Poland. Phenological observations were not performed during this period, due to the definitive end of birches flowering in Kraków.

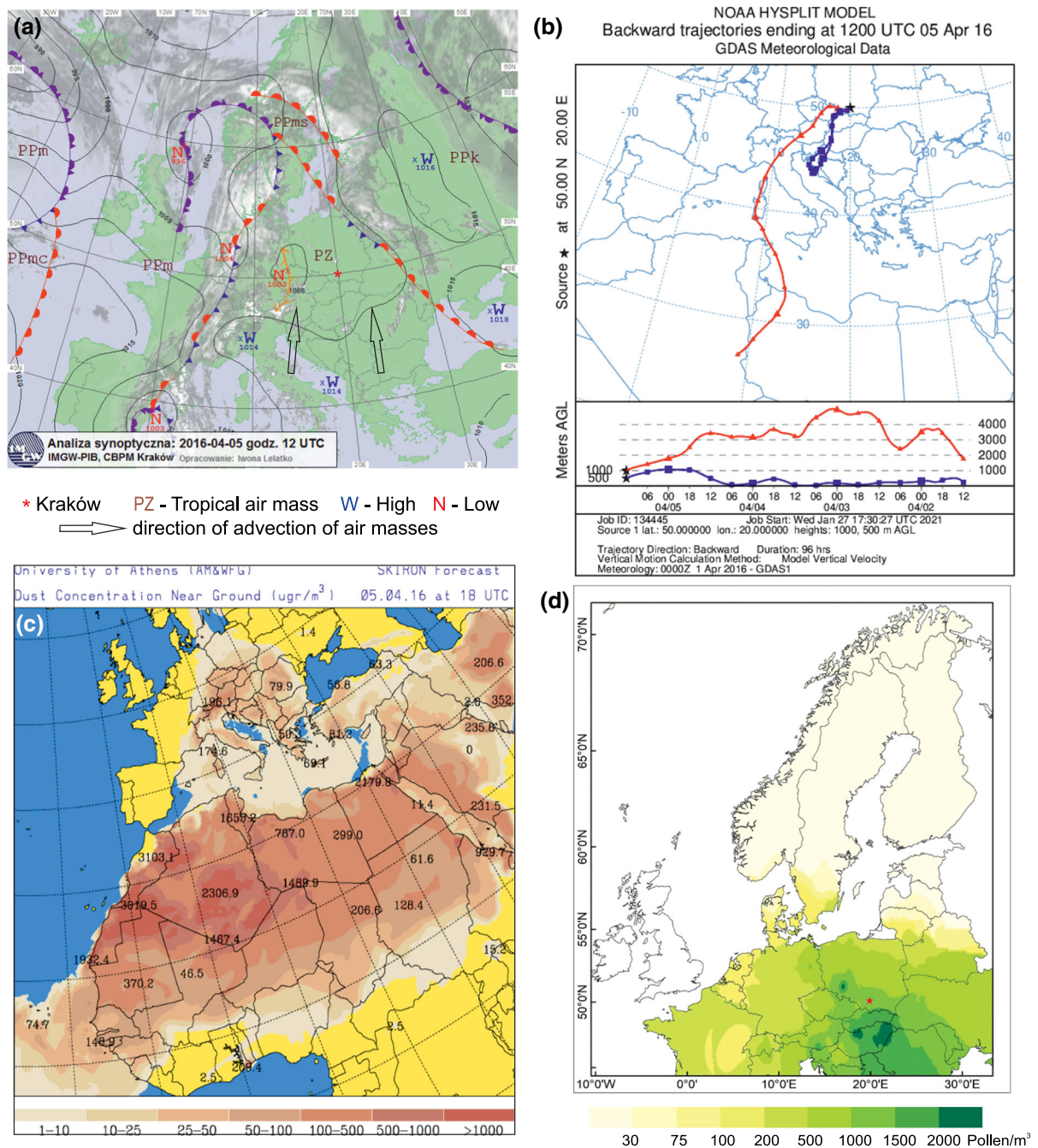


Fig. 5 Map of the synoptic situation (a), 4-day backward trajectories (b), dust concentration near ground (c) and daily birch pollen concentration (d) over Europe on April 5, 2016. Source: (a) Institute of Meteorology and Water Management–National Research Institute (IMWM-NRI) (www.pogodynka.pl), (b) HYSPLIT numerical model (<http://www.arl.noaa.gov>), (c) National and Kapodistrian University of Athens (from: crazynauka.pl), (d) author's own work on the basis of data from the providers

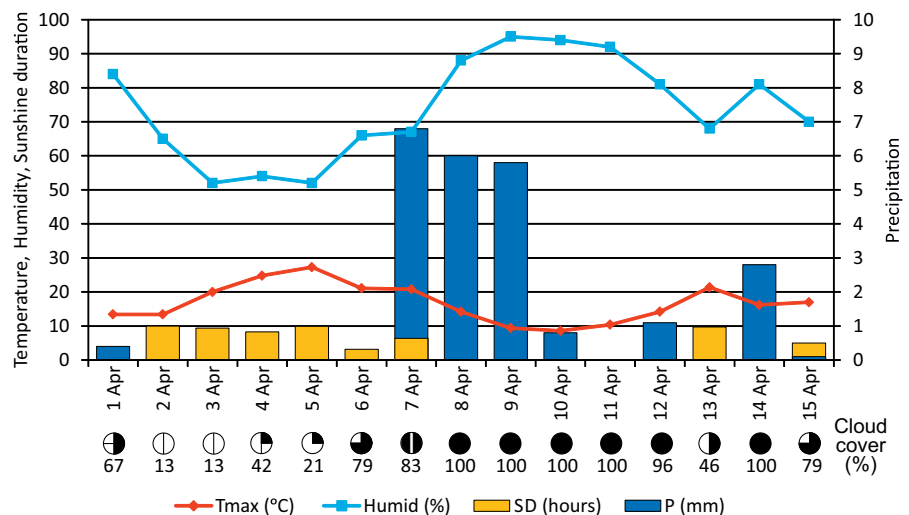
4 Discussion

Pollen seasons, as dynamic “systems,” are sensitive to even slight initial disturbances, caused by unstable weather conditions before or during pollen production, horizontal and vertical movements in the atmosphere and the movements of air masses on a large scale. The increased pollen exposure during the first episode was related to sources not of a local nature since the highest local pollen release can be observed during the full flowering (between 25 and 75% of open flowers) of birch trees, as confirmed and reported by other authors (Kasprzyk 2003, 2011; Puc & Kasprzyk 2013; Ranta et al. 2007; Siljamo et al. 2008; Stępańska et al. 2016). In addition, the weather conditions at the end of March were not appropriate to allow for rapid vegetation development and an intensive flowering of birch trees in the area of Kraków (low air temperature; $T_{\text{mean}} < 10^{\circ}\text{C}$). The pollen release could have started after 30 March, when temperature and sunshine levels increased and the first open flowers were observed. The study performed by Ranta et al. (2007) at five sites in Fennoscandia from 1997 to 2004 concluded that phenological observations of the birch leaf budburst overlap with the timing of the first half of the pollen season. However, phenological observations alone are not enough to determine the timing of the birch pollen season, because the LRT of pollen may also greatly affect the timing of the local birch pollen season. A study performed in Kraków for 18 observation years showed that single birch pollen grains were occasionally observed before the pollen season (Myszkowska

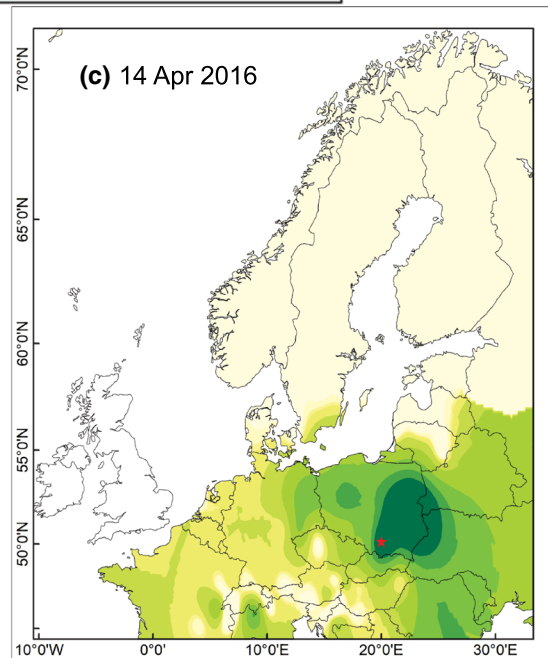
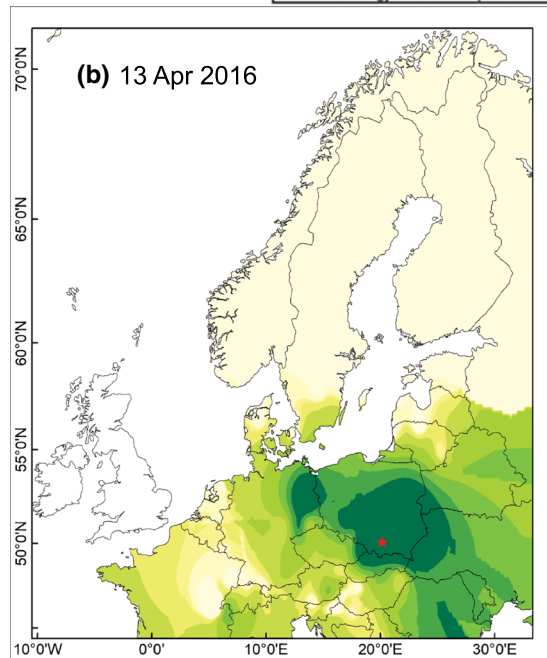
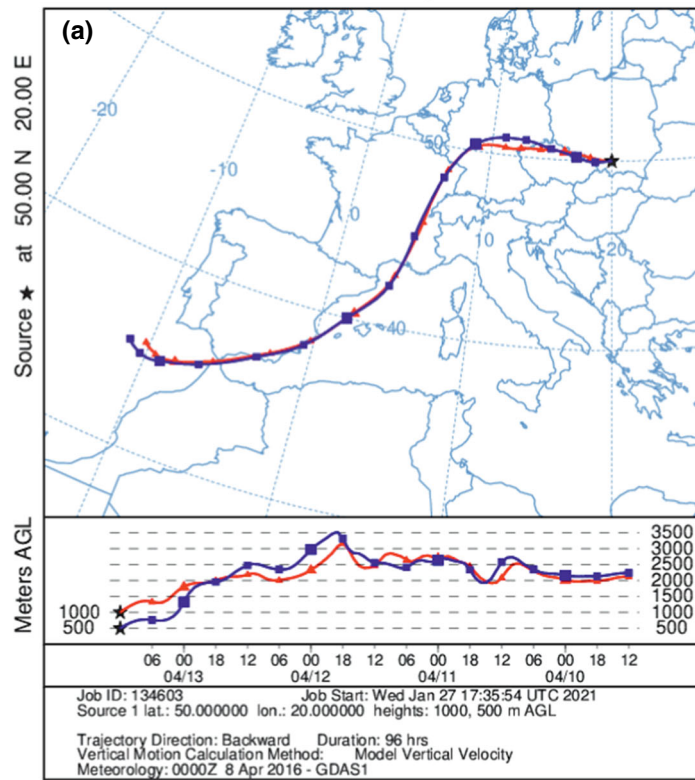
Fig. 7 4-day backward trajectories on April 13, 2016 (a) and daily birch pollen concentration (b–c) over Europe on April 13 and 14, 2016. Source: (a) HYSPLIT numerical model (<http://www.arl.noaa.gov>); (b–c) author’s own work on the basis of data from the providers

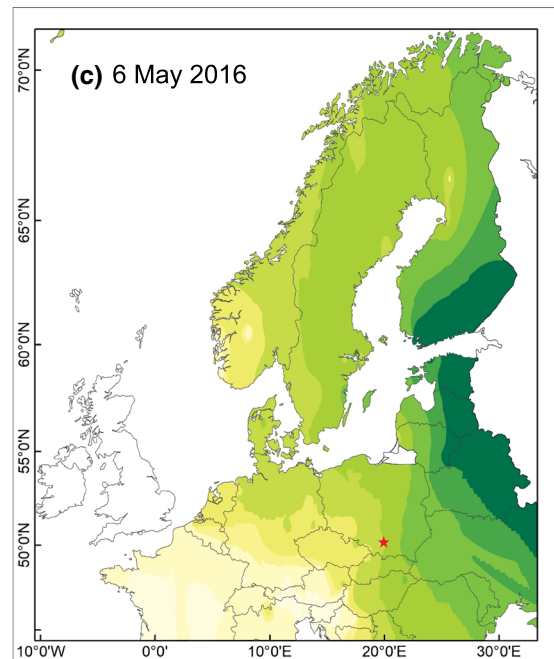
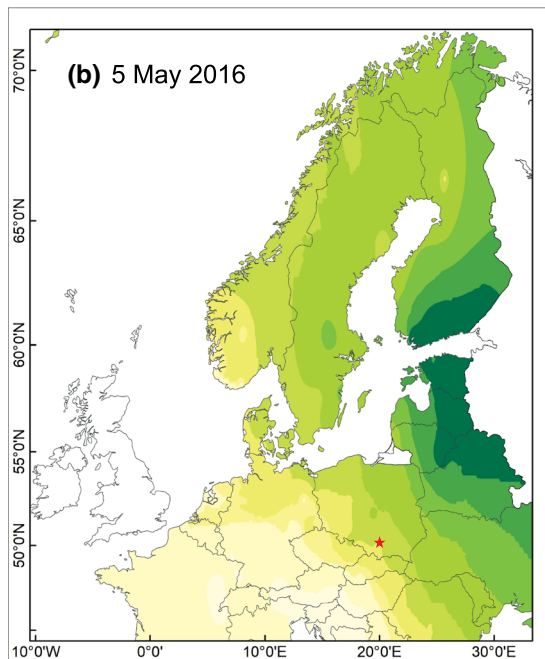
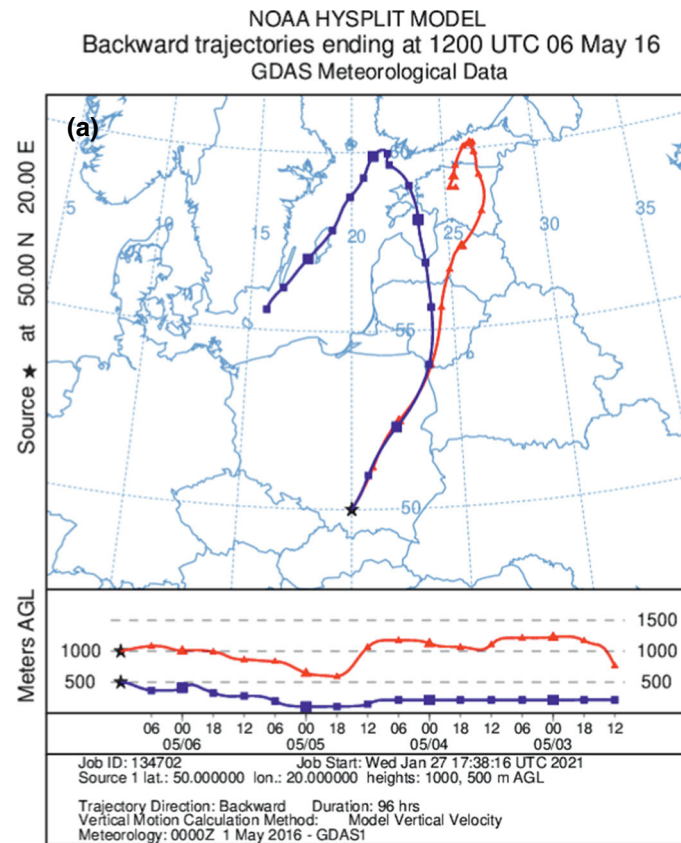
2013). A rapid increase in birch pollen concentrations would usually be attributed to the start of the pollen season. Considering the other Polish sites included in this study, it is seen that the earlier pollen concentration (> 20 Pollen/ m^3) was detected in Wrocław, on 3 April, followed by the pollen increase in Kraków and Rzeszów on 4 April (167 and 194 Pollen/ m^3 , respectively). The next day, 5 April, a very high pollen load (> 1000 Pollen/ m^3), was reported in Wrocław, Kraków and Sosnowiec (Fig. 4). Only in Poznań and Szczecin (northwestern Poland) did the LRT of birch pollen not have a significant impact on the beginning of the season, and thus, the season start was defined as a day with a slight increase in pollen concentration compared to the other pollen monitoring stations. Comparable studies from Russia (Moscow) and Finland, based on aerobiological and phenological observations from 1994 to 2005, emphasized that frequent events of pollen observations due to LRT from Russia could be identified before the local pollen season started in Finland, whereas vice versa transport episodes from Finland to Russia were of minor impact (Ranta et al. 2007; Siljamo et al. 2008). A similar situation was described in Copenhagen (Denmark), where in 2006 high bi-hourly pollen concentrations

Fig. 6 Daily course of selected meteorological elements on April 1–5, 2016: maximum temperature (Tmax; $^{\circ}\text{C}$), relative humidity (RH; %), precipitation (P; mm), sunshine duration (SD; hours), cloud cover (%)



NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 13 Apr 16
GDAS Meteorological Data





◀ **Fig. 8** 4-day backward trajectories on May 6, 2016 (a) and daily birch pollen concentration (b–c) over Europe on May 5 and 6, 2016. Source: (a) HYSPLIT numerical model (<http://www.arl.noaa.gov>); (b–c) author's own work on the basis of data from the providers

above 500 Pollen/m³ were observed before the local trees began to flower (Skjøth et al., 2007). In that study, Poland has been identified as a potential source region for LRT to Denmark, while in other years (2000–2005) also Germany was considered as a source country. Szczepanek et al. (2017) indicated a similar LRT event of Pinaceae pollen in May 2013 to Kraków (Southern Poland) from Ukraine, Romania, Hungary and Slovakia on the basis of synoptic situations, back trajectories and air mass advection.

Another factor identified in Kraków in 2016 was the influx of tropical air masses with a high content of particulate matter from North Africa and Southern Europe. This phenomenon of the long-lasting Saharan dust was presented by Baumann-Stanzer et al. (2019) and was used to investigate peak dust episodes over the Eastern Alpine region. The authors emphasized the importance of chemical weather forecasting because of serious health effects due to this phenomenon. The first episode of high birch pollen concentrations (5–8 April) could have been the threat for individuals sensitized to birch pollen, because birch pollen concentrations in 2016 exceeded the threshold values proposed by the EAACI group for clinical trials of allergen immunotherapy for pollen-induced rhinoconjunctivitis by Pfaar et al. (2017). Pollen exposure began rapidly, with daily concentrations exceeding several times the threshold value of 90 Pollen/m³ stated as provoking severe allergy symptoms (Samoliński et al. 2010). Due to the synergistic effect of allergens and the sand dust, an additional and increased reactivity of the upper respiratory tract could have been observed in allergic individuals, as reported by Ichinose et al. (2009).

The second pollen episode was related mostly to local pollen sources because it coincided with the full flowering of birch trees (from 25% up to all flowers blooming) in the middle of April in Kraków. Similar timing of the second peak of high concentration across Poland together with no indicators of LRT can also confirm the local origin of the pollen. Generally, the birch pollen seasons in Poland are slightly variable in

time (Grewling et al. 2012; Kubik-Komar et al. 2019; Myszkowska 2013, 2014; Myszkowska & Majewska 2014), and time of the highest birch pollen concentrations occurrence ranges from 15 April up to 20 April (SD = 6–8 days) as was confirmed by comparative, multicenter studies by Weryszko-Chmielewska (2014) and Puc et al. (2015). This season pattern is stable, as it was calculated for Kraków (V% = 6.19%) on the basis of a 20 year observation (Myszkowska & Majewska 2014).

The third episode was mostly related to LRT, but was less intense than the pollen influx at the very beginning of the pollen season. Several days with high pollen concentrations in the first week of May, especially after the main pollen season, do not occur regularly in Kraków (Poland). The retrospective analyses of birch pollen seasons in Poland, including 14 years of observations (2001–2014), showed that the pollen seasons ended on average between 1 and 13 May. The pollen concentrations usually start to decrease from the end of April (Myszkowska 2013). Single pollen grains may be observed even in October, but it is caused by the resuspension of pollen grains (Szczepanek 1994; Myszkowska & Piotrowicz 2009). The analyses of 18 pollen seasons in Kraków showed that the pollen season beginning was less variable in comparison with the season end (calculated using the 95% method) ($V = 7.36\%$ and $V = 11.71\%$, respectively), which was related to an extended fading of the pollen season (Myszkowska 2013).

As Siljamo et al. (2008) underlined, the analysis of the end of the season is more problematic due to the impact of local sources, which results in difficulties in reliably identifying LRT events. The authors reported that the flowering of the northern European birch forests in Finnish Lapland, Karelia, and northwestern Russia becomes evident in Moscow by the end of May, when the flowering has ended in all other regions. An illustration of such an impact has been presented by Sofiev and Siljamo et al. (2006), who have shown that pollen from Finnish and Swedish Lapland reached Denmark and Germany during one day on 7 June in 2005.

We would like to emphasize that our analyses follow the observations reported by Bogawski et al. (2019), who found that post-season LRT episodes of birch pollen to Poland were mainly recorded in the first fortnight of May in 1997–2016. The main source areas of transported pollen were western Russia, Belarus

and to a lesser extent the eastern Baltic republics and the Scandinavian Peninsula. A high-pressure center located over Scandinavia favored the pollen transport in most of the cases. The authors stressed that these episodes may be extremely severe, thereby prolonging and strengthening the exposure to birch pollen allergens, but this was not observed in our study.

5 Conclusions

1. The unusually high birch pollen concentrations in Southern Poland, especially in Kraków, observed in 2016, were largely caused by LRT of pollen material carried by the air masses from the Souths (Serbia, Hungary, Austria, the Czech Republic, Slovakia), where the birch full flowering was occurring. Among the three studied episodes, the close relationship between the higher pollen concentration and the pollen influx into Poland was clearly confirmed in the case of the first of them, noted at the very beginning of the pollen season, in the first days of April. The second episode was recognized as a result of the local flowering during the full pollen season, while the third one was mostly related to the long-range pollen transport from the Baltic Fennoscandia (Finland), most probably Russia and the Baltic countries (Lithuania). In the case of the unusual increase in pollen concentrations within the pollen seasons, the local sources and the physiological features of birches should be primarily considered.
2. The unexpected pollen inflow at the very beginning of the birch pollen season in 2016 can be associated with advection of tropical air masses from the south and the center of Europe to the north.
3. The LRT of pollen grains must be taken into account when forecasting the birch pollen risk relevant for allergic patients. This is necessary in order to take steps to minimize symptoms severity in patients, who could be unaware of relevant exposures during time of the influx. Pollen allergy sufferers and people with respiratory and circulatory system diseases should reduce time of outdoor activities to the necessary minimum, due to the possibility of a synergy of allergens and solid particles (mechanical irritation of the upper respiratory tract and conjunctiva).

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Declarations

Conflict of interest No conflict of interests has been declared.

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