



High *Ambrosia* pollen concentrations in Poland respecting the long distance transport (LDT)

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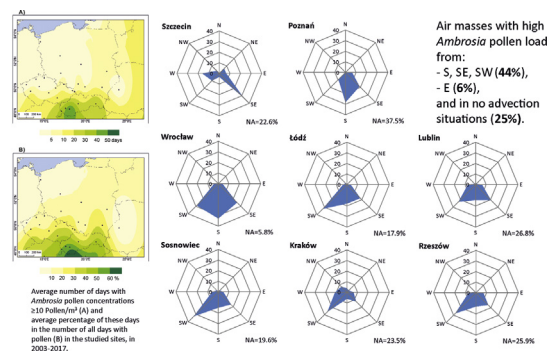
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HIGHLIGHTS

- *Ambrosia* pollen influx into Poland was studied.
- Back trajectory analyses were performed for selected sites.
- High *Ambrosia* pollen concentrations were associated with direction of air masses.
- The most frequent pollen influx was observed from prevailing southerly direction.
- In 2014 the pollen transport from the easterly direction dominated.

GRAPHICAL ABSTRACT



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ABSTRACT

High *Ambrosia* pollen concentrations in Poland rather rarely come from the local sources. The aim of this study was to define the temporal and spatial differences of the high *Ambrosia* pollen concentrations by creating models for the pollen transport from the distant sources. This study was thought to determine the direction of the air masses inflow into Poland, carrying *Ambrosia* pollen, from areas of the bordering countries with the pollen concentrations higher than iSTOTEN_n Poland. Pollen and meteorological datasets at 8 monitoring sites in Poland,

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and daily pollen concentrations at 11 sites in the Czech Republic, 5 sites in Slovakia and 3 sites in Ukraine were analysed recently. Days with concentrations ≥ 10 Pollen/m³ and concurrent meteorological situations were analysed in great deal. The HYSPLIT model was applied to compute backward trajectories up to 4 days backward (96 h) and at three altitudes: 20, 500 and 1000 m above ground level (a.g.l.). High pollen concentrations occur most frequently when the air masses inflow into Poland from southerly (S, SE, SW, 44%) and easterly (E, 6%) directions and in no advection situations (25%). In years with the highest frequency of days over 10 Pollen/m³, the prevailing directions of the pollen influx into Poland were from the South (2004–2006, 2008, 2011) but in one year (2014) from the East. Trajectories for the studied period show that air masses come most frequently from Slovakia and the Czech Republic. Sometimes, the *Ambrosia* pollen transport happens from Ukraine.

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1. Introduction

Ambrosia is a highly allergenic, anemophilous member of the Asteraceae family which is one of the largest families of plants. The *Ambrosia* genus is composed of about 40 species but only five species have been noted in Europe: *Ambrosia artemisiifolia* L. = *A. elatior* (short or common, annual ragweed), *Ambrosia trifida* L. = *A. aptera* DC (great or giant ragweed), *Ambrosia psilostachya* Torr. et Gray = *A. coronopifolia* (perennial ragweed) and *Ambrosia tenuifolia* Spreng. (silver ragweed). *Ambrosia maritima* L. is the only native species in Europe and occurs in the Mediterranean region (Hansen, 1976). The other four species are native to eastern and central North America. It favours human activity places and colonizes cultivated fields and ruderal habitats, grows along roadsides, near elevators and harbours. Each plant produces a huge number of pollen grains, containing one of the most potent allergens known (Comtois, 1998; Weryszko-Chmielewska and Piotrowska, 2008). The areas most contaminated with ragweed in Europe are Hungary, Croatia, the Lyon area in France, northern Italy, especially the North-West regions of Piedmont and Lombardy and the North-

East regions of Veneto and Friuli-Venezia Giulia, Switzerland, Austria, the Czech Republic, Bulgaria, Slovakia and also Ukraine (Dechamp et al., 1997; Dahl et al., 1999; Rybniček et al., 2000a; Mosyakin and Yavorska, 2002; Juhász et al., 2004; Clot, 2003; Makra et al., 2004, 2005; Peternel et al., 2005, 2008; Cecchi et al., 2006; Smith et al., 2013; Thibaudon et al., 2014; Karrer et al., 2015; Hrabovský et al., 2016; Skálová et al., 2017; Rodinkova et al., 2014, 2018). In Poland, the most frequently found species is *Ambrosia artemisiifolia* L. which occurs commonly in the western and south-western parts of the country (Tokarska-Guzik et al., 2011; Stępańska et al., 2017; Zajac and Zajac, 2019). The progress in the distribution of this invasive species up to 2019 in Poland has been presented as follows, on the maps by Tokarska-Guzik et al. (2011), updated version published by Stępańska et al. (2017) (Fig. 1) and by Zajac and Zajac (2019). Between 2013 (Fig. 1) and 2019 (Zajac and Zajac, 2019), several more *A. artemisiifolia* sites were found in the eastern and southern part of the country. According to the last report on invasive species in Poland, presented by General Directorate for Environmental Protection, in the recent years, *A. artemisiifolia* has dynamically increased its occurrence area and the

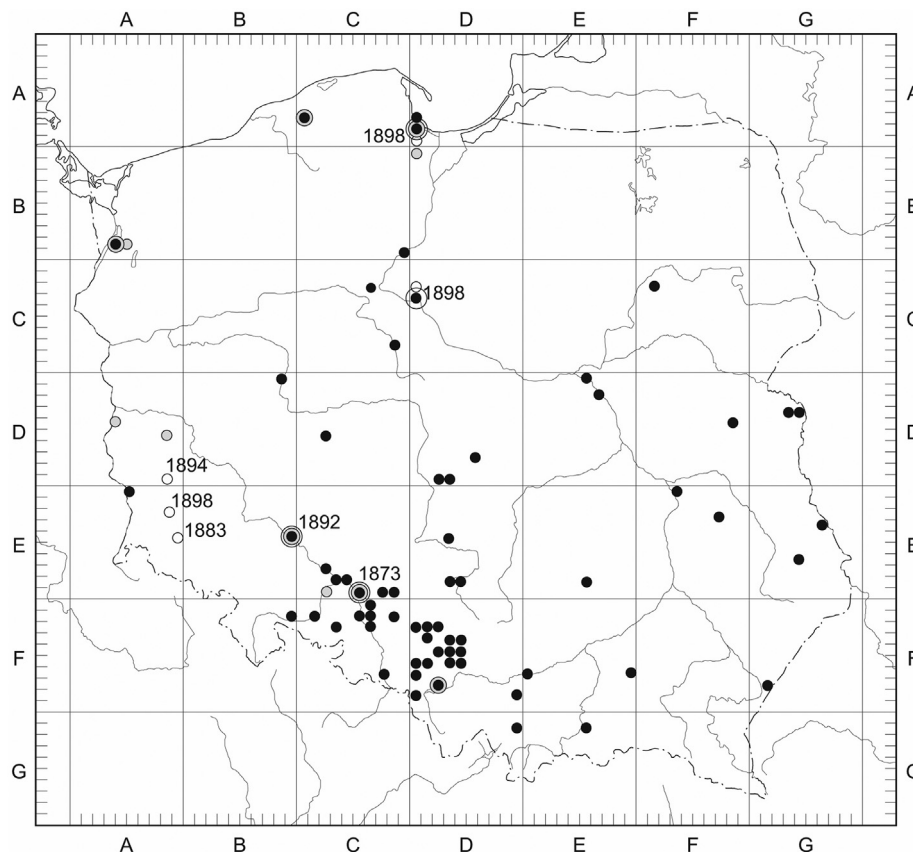


Fig. 1. Recorded history of the spread of *Ambrosia artemisiifolia* L. in Poland drawn for the consecutive time periods. White circles: between 1851 and 1900; Grey circles: between 1901 and 1950; Black circles: between 1951 and 2013. Updated map published by Tokarska-Guzik et al. (2011), given after Tokarska-Guzik approval.

progressive expansion of this species is expected in Poland in the nearest future (Bzdęga et al., 2018).

Annual totals of ragweed pollen grains approach nearly 20,000, including daily average 2000 Pollen/m³ during the ragweed pollination season in the southern part of Hungary (Járai-Komlódi, 2000). Cecchi et al. (2006) suggested that the possible source area for *Ambrosia* pollen noted in central Italy is Hungary. In France and Hungary ragweed pollen is the common source of allergy symptoms during late summer (Dahl et al., 1999). For allergy patients it is important to know the ragweed pollen concentration forecast in advance, which makes the treatment easier and more effective. Knowledge on ragweed source areas and air masses trajectories improves the precision of forecasts (Skjoth et al., 2010). These source areas influence other European regions, including Poland, with pollen transported for long distances (Smith et al., 2008; Kasprzyk et al., 2011; Šikoparija et al., 2013). Episodes of the long distance pollen transport are generally irregular (Smith et al., 2008) and can alter the course of the pollen season (Sofiev et al., 2006). The distribution of ragweed seems to be limited by climate, even when its establishment is allowed by the human environment (Comtois, 1998; Saar et al., 2000). Temperature and the photoperiod govern the distribution of *Ambrosia*. It is a short day plant i.e. its flowering begins in late summer and early autumn, when average temperature of 14–15 °C in August–September is the main factor influencing this distribution (Reznik, 2009). In northern countries of Europe, (Denmark, Sweden) the *Ambrosia* presence is noted sporadically because the vegetative season is too short for seed maturation (Comtois, 1998; Dahl et al., 1999; Sommer et al., 2015). However, a process-based model of weed growth, competition and population dynamics predicted a northward shift in the available climatic niche for *Ambrosia artemisiifolia* populations. Over the next 50 years, a risk of increased health problems caused by ragweed pollen in UK and Denmark is expected (Storkey et al., 2014). In southern Europe (Spain, southern Italy) where long, dry and hot summer causes the air and soil desiccation, climate does not trigger the ragweed growth (Allard, 1945; Matyasovszky et al., 2018).

The sensitization to *Ambrosia* pollen in Europe has become a great problem and it is still on the steady increase. According to clinical studies, ragweed pollen could have induced asthma approximately twice as often as it occurs in other pollen allergies (Gadermaier et al., 2004; Smith et al., 2013). Asero (2002) reports increasing sensitization rates to ragweed pollen, from 20% to >60% in a five year period in the Milan area. Clinical studies performed in Austria proved that the higher ragweed pollen concentrations the higher the amount of ragweed pollen antibodies in the blood of patients who suffer from inhalant allergy (Jäger and Litschauer, 1998). In northern Italy *Ambrosia* pollen provoked oculorhinitis and asthma symptoms from August to October (Zanon et al., 2002).

In Poland, the problem of ragweed sensitization seems to be not evident, but there is a lack of new reports regarding that problem. The results obtained in the 1990s in Krakow pointed out the readiness of the local population to the immunological response to ragweed allergens (Obtułowicz et al., 1995). The analyses performed in Łódź (central Poland), in 2003–2006 in the group of 181 patients with potential allergy, indicated the rate of sensitization to ragweed pollen around 40% (Kozłowska et al., 2007). In the neighbouring countries, the percentage of patients sensitive to ragweed allergens is various. The study performed in Bratislava (Slovakia) confirmed ragweed sensitization in 21.3% and 13.9% of patients in 2002 and 2003, respectively (Ščevková et al., 2015), which was comparable to the previous paper (Hrubíško, 1998). Skin prick tests (SPT) and/or specific IgE measurements with ragweed allergens carried out in 94 children with pollen allergy in the Brno region (the Czech Republic) in 1995 and in around 200 adult allergic people per year in 1995–1997, showed the positive skin reaction or higher specific IgE to ragweed in 22% of children and in about 20%–25% of adults (Rybníček et al., 2000b). The other study showed, that about 35% of pollen-allergic patients in Prague and about 25%–30% in Brno indicated positive SPT to ragweed allergens (Rybníček et al., 2000a).

In Ukraine, the sensitivity to *Ambrosia* allergens was investigated using the molecular ALEX test, applying three available components (Amb a 1, Amb a, and Amb a 4). In the group of 1011 individuals, 34.95% showed the higher IgE concentration against *Ambrosia* allergens (Rodinkova and Yuryev, 2019). The results obtained in Poland and adjoining countries indicate that, the percentage of sensitization to ragweed is not currently frightening. However, scenarios of the increase in pollen allergy in Europe, published in 2017 (Lake et al., 2017) showed, that in 2041–2060 in Poland and the neighbouring countries, the number of populations sensitized to ragweed could reach about 1000 in Slovakia, 2000 in the Czech Republic and up to 4500 in Poland.

In different countries, authors reported various threshold values of ragweed pollen concentrations which could induce the allergy symptoms. The threshold value was defined as 5 pollen grains per m³ of air (Pollen/m³) (Dechamp et al., 1997) or 13 Pollen/m³ (Laaidi and Laaidi, 1999) in France, 5 Pollen/m³ (Comtois and Gagnon, 1998) in Canada, 20 Pollen/m³ (Jäger, 1998) in Austria, 30 Pollen/m³ (Makra et al., 2005) or 50 Pollen/m³ (Juhász et al., 2004) in Hungary, but independently on the threshold value, it was stressed that even very low pollen concentrations can provoke symptoms in allergic people (Bergmann et al., 2008; Sommer et al., 2015). High *Ambrosia* pollen concentrations were most often noted on days when the air masses inflow into Poland from East and South-East, and from South and South-West (Kasprzyk, 2008; Kasprzyk et al., 2011; Šikoparija et al., 2013; Stępańska et al., 2017; Grewling et al., 2019). Some authors suggest the source areas of *Ambrosia* pollen indicating air masses directions and calculating backward trajectories, but rarely these studies take into account the pollen concentration in the source area (Cecchi et al., 2006; Chłopek et al., 2011; Kasprzyk et al., 2011). Therefore in this study we included data not only from the receptor area (Poland) but also from neighbouring areas i.e. from Slovakia, the Czech Republic and Ukraine. The distance of 50–100 km is assumed to be the natural dispersal rate of airborne pollen grains, but the distance exceeding 200 km is included as typically related to the long distance transport (Orlanski, 1975; Smith et al., 2013). As LDT is related to a synoptic scale, the pollen transport should be treated as the typical synoptic scale process about 200 km and more.

The aim of the study was to define the temporal and spatial variations of the high *Ambrosia* pollen concentrations at the selected sites in Poland by creating models for the pollen transport from the remote sources.

2. Materials and methods

2.1. Aerobiological data

In this study we investigated pollen inventories for the presence of *Ambrosia* pollen in adjoining countries. Pollen and meteorological datasets were used at 8 monitoring sites in Poland and daily pollen concentrations at 11 sites in the Czech Republic, 5 sites in Slovakia and 3 sites in Ukraine in 2003–2017 (Fig. 2). The special attention was paid to days with concentration ≥ 10 Pollen/m³ and meteorological situations, that accompanied them.

The aerobiological measurements were carried out using volumetric pollen traps of the Hirst design (Hirst, 1952). Air was sucked into the trap at a rate of 10 l/min through an orifice of 2 mm $\times$ 14 mm. The air behind the orifice flows over the rotating drum which moves at 2 mm/h and is coated with an adhesive transparent tape (Melinex). The tape used for catching pollen grains was replaced every week. Airborne pollen grains were scanned and counted using a light microscope at 400 $\times$ magnification. Following the removal of the tape from the trap, the tape was cut into segments corresponding to 24 h periods. Pollen grains were counted according to the standard methods by the Spanish Aerobiology Network (REA; Galan et al., 2014). Results were expressed as a daily average of pollen grains per cubic metre of air (Pollen/m³) (Galan et al., 2017). To ensure the robustness of data only days with pollen concentration ≥ 10 Pollen/m³ were taken into account in statistical analysis.

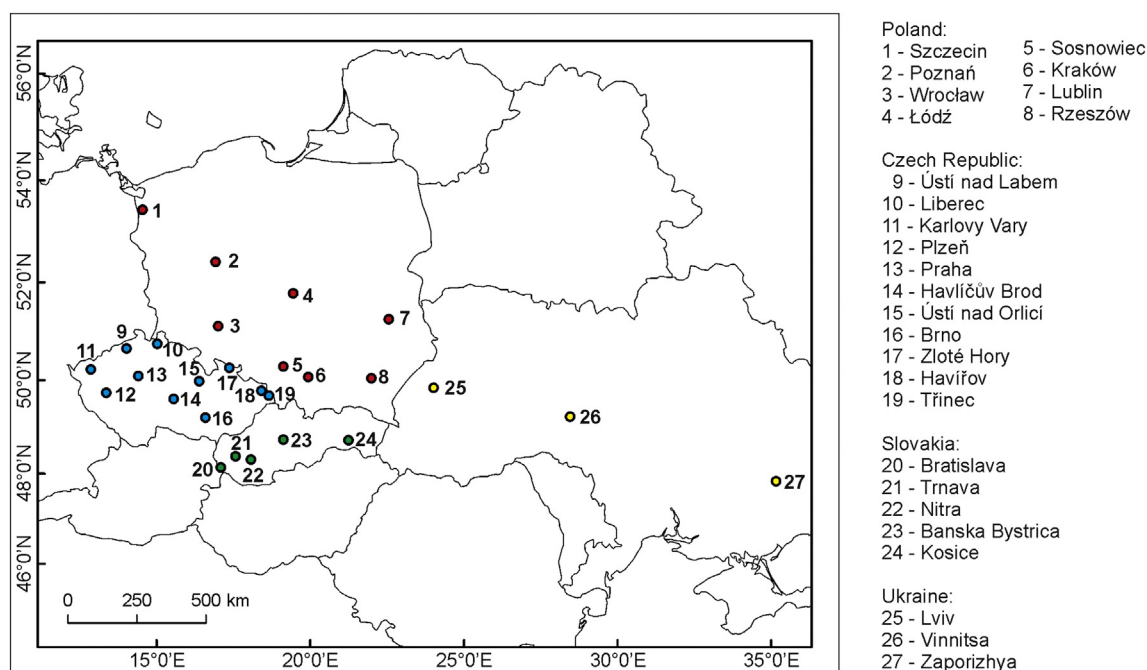


Fig. 2. Location of pollen monitoring sites employed in the study

The potential events of the long distance transport to Poland were selected as follows:

- using the daily *Ambrosia* pollen concentrations obtained at each of the eight selected sites in Poland, in 2003–2017, the average number of days with the high (≥ 10 Pollen/ m^3) pollen concentrations was calculated for each year and for each site (see Table 1);
- then we have decided to choose, for the backward trajectory analyses, the events at the days with the concentration ≥ 10 Pollen/ m^3 observed in a given year, at two sites at least (2004–2006, 2008, 2011, 2014);
- days with the concentration ≥ 10 Pollen/ m^3 observed in the selected years were confronted with the high pollen concentrations in the previous 1–5 days at the other sites, including foreign sites to estimate the probability of the long distance pollen transport and their potential direction.

2.2. Backward trajectory analyses

The Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) was used to compute the paths (so-called backward

trajectories) of moving air particles calculated 96 h backward at 6 h interval and at three different altitudes: 20, 500 and 1000 m above ground level (a.g.l.). This system was created by the NOAA (Air Resources Laboratory; <http://www.arl.noaa.gov>) (Stein et al., 2015). The data (with a spatial resolution 1×1 degree; GDAS1) used to calculate the backward trajectories come from the operational systems GDAS (Global Data Assimilation System; <http://www.arl.noaa.gov>), which are often used to study the movement of the air masses.

The choice of a 4 day period resulted from time needed for transformation of air masses (minimum 3 days, Barry and Carleton, 2001) and the need to check trajectories of substantial length. According to Sofiev et al. (2013) the atmospheric lifetime of pollen grains is a few days (due to substantial gravitational sedimentation). Previous studies (Cecchi et al., 2006; Šikoparija et al., 2013; de Weger et al., 2016; Grewling et al., 2019) showed that ragweed pollen transported from distant sources needs around 2–3 days to reach a receptor area located several hundred kilometers away. We used trajectories at three heights to take into account characteristics of these heights in troposphere, at which pollen grains could be translocated from the local, intermediate and remote sources. HYSPLIT, the atmospheric transport model is

Table 1

Average number of days with the highest *Ambrosia* pollen concentrations at studied sites in Poland in 2003–2017.

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Szczecin	5	3	14	8	4	4	7	13	11	12	4	19	0	0	7
Poznań	0	0	14	26	8	7	9	5	17	0	10	16	8	9	4
Wrocław	30	29	29	22	8	6	15	0	11	7	0	39	25	19	17
Łódź	0	12	36	13	9	29	4	18	16	12	0	17	19	22	17
Sosnowiec	18	28	17	26	8	24	20	8	20	10	4	22	14	18	15
Kraków	25	19	6	3	3	34	25	6	31	22	9	25	19	16	12
Rzeszów	31	43	32	33	25	21	29	17	30	14	7	37	28	29	24
Lublin	14	20	23	18	10	26	12	15	12	6	0	30	13	13	26

Columns in orange - years with high pollen concentrations, taken for further analyses; red - sites with the highest pollen concentrations in a given year; green - a year with the lowest pollen concentrations.

usually applied in aerobiology to determine potential sources of plant pollen such as *Quercus* pollen in southern Spain (Hernández-Ceballos et al., 2011), *Ambrosia* pollen in European countries (Stach et al., 2007; Smith et al., 2008; Kasprzyk et al., 2011) and *Betula* pollen in central and northern Europe (Skjøth et al., 2007). The investigation of the air masses movement requires data from the operational systems GDAS (Global Data Assimilation System; <http://www.arl.noaa.gov>). More information on the HYSPLIT model deliver Draxler (1999) and Stein et al. (2015). The practical application of the HYSPLIT model in the aerobiological studies was presented, among others, by Šikoparija et al. (2013), Fernández-Rodríguez et al. (2014, 2015), Jochner et al. (2015), de Weger et al. (2016) and Bilińska et al. (2017).

The level of 1000 m a.g.l. reflects the lower boundary of the free atmosphere where the phenomenon of earth surface friction is vanishing (Stull, 1988; Oke, 1995). Pollen at this height can be transported for the long distances (LTD). This height was accepted in our study because of the montane barrier of the Carpathians and Sudetes in the southern part of Poland. At this height, the mountain barrier does not prevent the transport of pollen. At the transitional level of 500 m a.g.l. pollen could come from both the long distance transport and local sources, then it could be a result of convection (raising of warmth) and turbulence (whirling of air). In addition, we should add that this range of altitudes (ground level, 500 m, 1000 m) is a common approach in many studies dealing with the pollen transport (Šikoparija et al., 2013; de Weger et al., 2016; Bilińska et al., 2017).

The lowest altitude (20 m) corresponds to the height of the volumetric sampler position (20–40 m a.g.l.). If backward trajectories were generated at 20 m a.g.l. then some disparities in air directions can occur, resulting from changes of convection movements, friction forces and landforms (Hernández-Ceballos et al., 2014).

Maps presented in this study were produced in ArcGIS Software. The data were drawn for the days applying the radial basis functions (RBF) method. It is an exact interpolation technique, which takes into account general tendencies and the local variability. It is used to produce smooth surfaces from a large number of data points. The functions produce good results for gently varying surfaces.

The backward trajectories were figured out for the days with the concentration ≥ 10 Pollen/m³ at two sites at least, in each studied year. Three groups of the days with the different air masses directions, from: southerly, easterly directions and in no advection situation were singled out (shown as examples in the Results section).

Additionally, the synoptic maps showing the spatial distribution of air pressure, atmospheric fronts and direction of air masses advection, and calendar on circulation types of atmosphere in Poland by Niedźwiedz (2019; <http://klimat.wnoz.us.edu.pl>) were used. The maps mentioned above, were obtained from the Deutscher Wetterdienst Offenbach (DWD; www1.wetter3.de) database and Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB; <http://www.imgw.pl>).

3. Results

The highest average number of the analysed days, with ragweed pollen concentrations ≥ 10 Pollen/m³, was observed in Rzeszów, while the relatively high values were recorded also in Lublin, Kraków and Sosnowiec (Fig. 3A). The spatial distribution of the average number of days with concentration ≥ 10 Pollen/m³ is presented on the map, where the longest period of the high pollen concentration occurred in Slovakia (about 40 days) compared to about 7–10 days at sites in the southern part of Poland (Fig. 3A).

In Poland, the average ratio of days with concentrations ≥ 10 Pollen/m³ to the total number of days when ragweed pollen was recorded, the highest value was in Rzeszów and the lowest in Poznań and Szczecin (Fig. 3B). The highest average percentage of days with discussed pollen concentrations was noted in the Czech Republic (about 40%) and in Slovakia (about 60%), compared to about 30% at sites in Poland

(Fig. 3B). Taking the average percentage of days with high pollen concentrations in studied years into consideration, the highest value in Poland was recorded in 2014 and the lowest one in 2013 (Fig. 4). The continuation of this diagram is the arrangement of the average number of days with high pollen concentrations (≥ 10 Pollen/m³) at studied sites, which highlights years that were selected for further analysis regarding the pollen transport in 2004–2006, 2008, 2011 and 2014 (Table 1). In 2014 high pollen concentrations were mainly observed in Wrocław, Rzeszów and Lublin. Somewhat lower values were noted in 2004–2006 and again Wrocław and Rzeszów dominated (Table 1).

Analyses of backward trajectories calculated for a few cities in the southern part of Poland, for Wrocław, Sosnowiec and Rzeszów indicate pollen coming from the Czech Republic and Slovakia as we could see an example of the path of the backward trajectory for Wrocław on 7 September 2005 (Fig. 5). The backward trajectories for the central sites (Wrocław and Poznań) indicate the pollen transport also from the southerly directions, as the example of the backward trajectory for Wrocław shows on 13 September 2006 (Fig. 5). Before that time high *Ambrosia* pollen concentrations were recorded at sites in the Czech Republic and western Slovakia. Backward trajectories for Lublin on 6 September 2008 illustrate the pollen transport also from the southerly directions (Fig. 5). Before that date, at the end of August, high pollen concentrations were noted at some sites in Slovakia (Fig. 5).

In 2011 high *Ambrosia* pollen concentration episodes occurred several times, in August between 18 and 20 and between 24 and 31, and in September between 4 and 5 and between 11 and 12 (Fig. 6). These episodes were relevant to the air advection from the southerly direction, which evidenced high pollen concentrations in Slovakia and the eastern part of the Czech Republic in the first week of September.

In 2014 at the beginning of September, the cascade pollen influx into Poland from the easterly direction was observed. At the end of August, high pollen concentrations were noted in eastern Ukraine, Slovakia and the Czech Republic. Backward trajectories for Rzeszów on 2 September and for Wrocław on 3 September indicate the pollen transport from the easterly directions, from Ukraine (Fig. 7). Backward trajectories for Szczecin on 5 September show similar directions of the pollen transport (Fig. 7). Unfortunately, the isoline range with high pollen concentrations in eastern Ukraine (Vinnytsa, Zaporizhzhia) is missing on presented maps (Fig. 7). It was impossible to place those, being 600 km away from each other, sites on the map because then isolines could give a misleading picture as they could be interpolated at sites from which pollen data were missing (Estonia, Lithuania, Latvia, Belarus). If pollen data are missing on so large area then isolines could not reflect the real picture. The diagram of pollen concentrations noted at Polish and Ukrainian sites confirms high *Ambrosia* pollen concentrations at sites located in the eastern part of Ukraine (Fig. 8).

High *Ambrosia* pollen concentrations depend on meteorological conditions. High concentrations occurred most often when air masses approached monitoring sites in Poland from southerly (S, SE, SW; 44%) and easterly (E; 6%) directions and in no advection situations (NA; 25%) (Fig. 9). Missing value of 25% means a few days when the air advection from other directions was of no great frequency.

4. Discussion

A 15 year study on the *Ambrosia* pollen occurrence in Poland revealed that *Ambrosia* pollen seasons were hardly ever consistent, which probably resulted from scarce pollen sources occurring mainly in the south-western part of Poland (Tokarska-Guzik et al., 2011; Zając and Zając, 2019). In areas where ragweed generally appears, pollen seasons are dense (Jäger, 1998, 2000; Petermel et al., 2005, 2008), while in other areas the high concentrations in the season indicate pollen incoming with air masses by the long distance transport (Saar et al., 2000). The scattered dispersion of ragweed populations causes that *Ambrosia* pollen occurrence in Poland depends mainly on the long distance transport (Stach et al., 2007; Smith et al., 2008). The lack of one compact

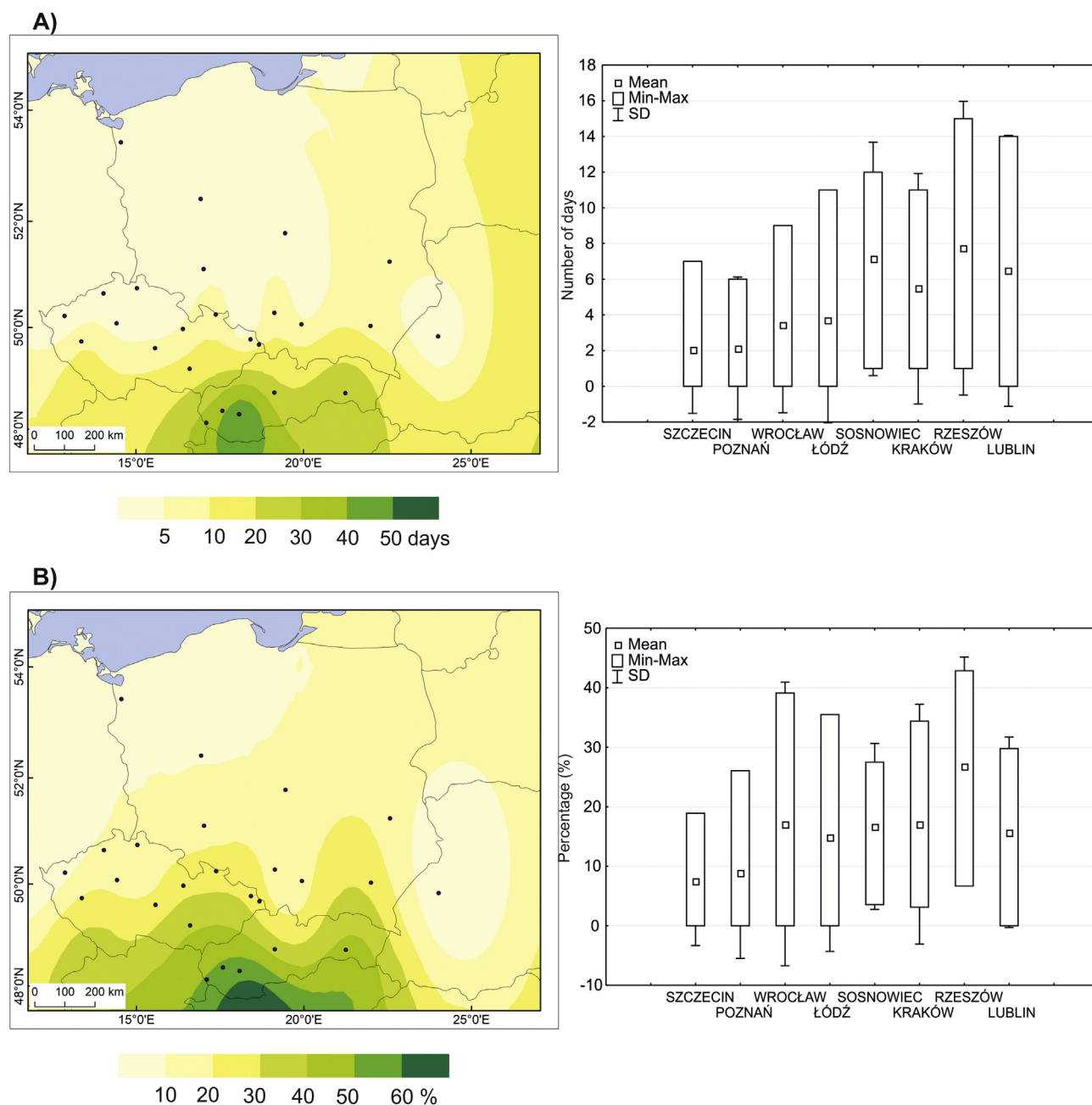


Fig. 3. Average number of days with *Ambrosia* pollen concentrations ≥ 10 Pollen/ m^3 (A) and average percentage of these days in the number of all days with pollen (B) in 2003–2017.

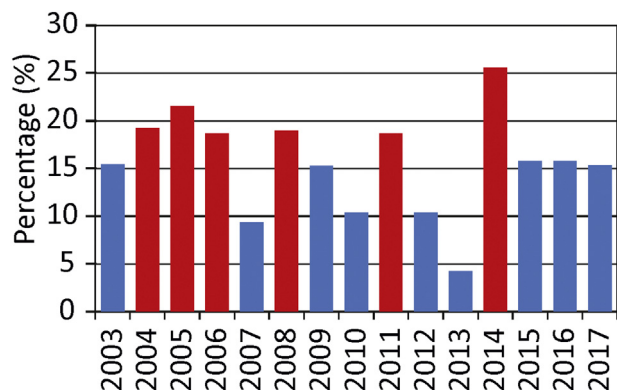


Fig. 4. Average percentage of days with pollen concentrations ≥ 10 Pollen/ m^3 in the number of all days with pollen in Poland, in 2003–2017.

period of ragweed pollen occurrence in Poland allowed to suppose, that pollen comes from sources other than local ones (Piotrowska and Weryszko-Chmielewska, 2006). The capability of *Ambrosia* pollen grains to travel long distances means, that *Ambrosia* pollen from heavily invaded areas could be liable for high, harmful concentrations in regions, where the plant sources are scarce (Šikoparija et al., 2009; Prank et al., 2013). On the way, pollen transported from distant sources is still immunoreactive (possess reactive Amb a 1) (Grewling et al., 2016; Celenk, 2019). In our study we analysed the phenomenon of pollen transport from three countries and 15 sites with the maximum distance of 1700 km (Szczecin-Zaporizhyya), according to the recommended distance above 200 km, considered as the long distance transport of pollen (Orlanski, 1975; Smith et al., 2013). Our considerations also coincide with the other authors, who referred the long-distance transport (or long-range transport) to the atmospheric processes over 1000 km (Seinfeld and Pandis, 2006).

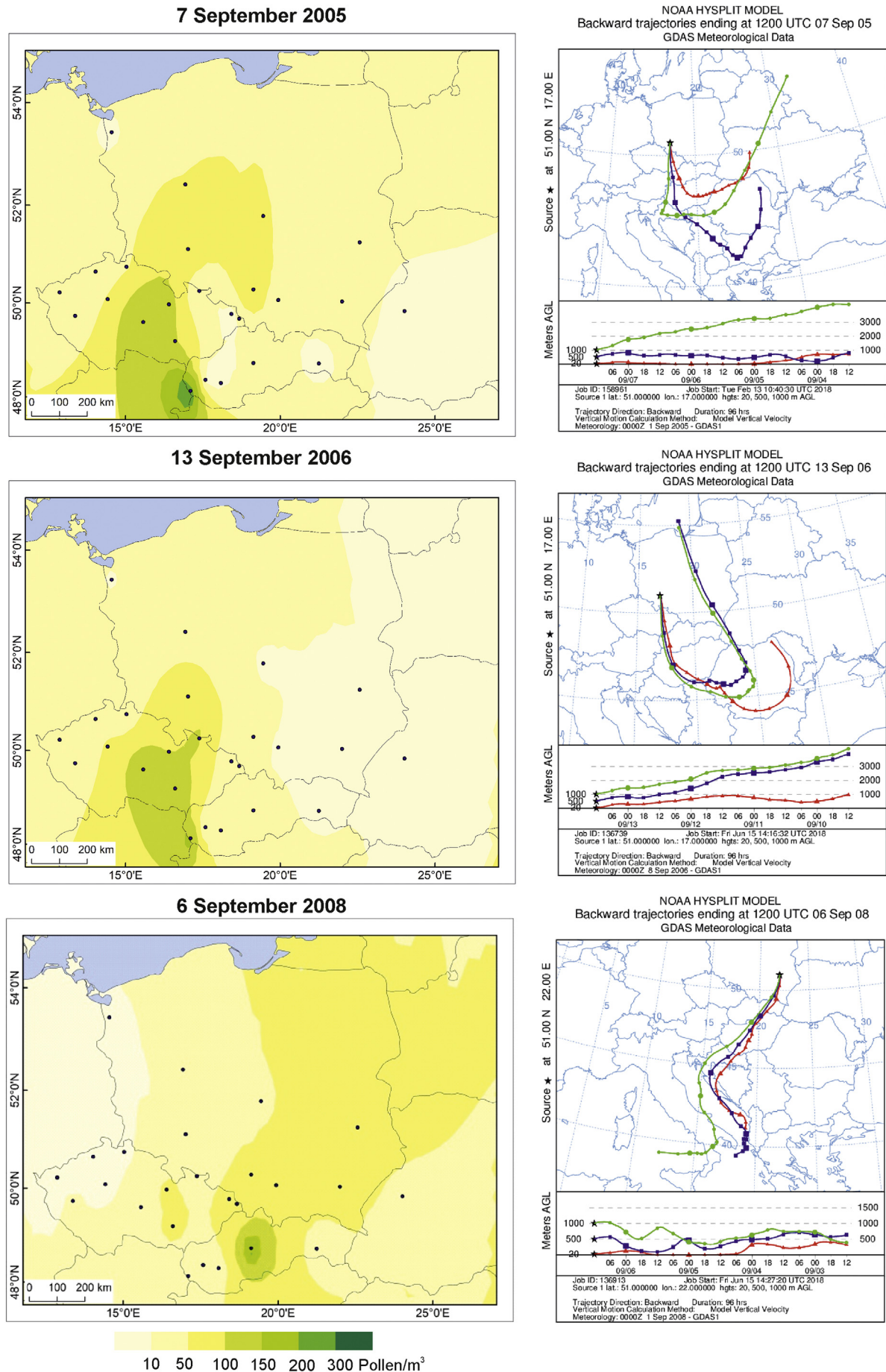


Fig. 5. Daily *Ambrosia* pollen concentrations at selected sites in Poland, Ukraine, Slovakia and the Czech Republic from 15 August to 14 September 2011.

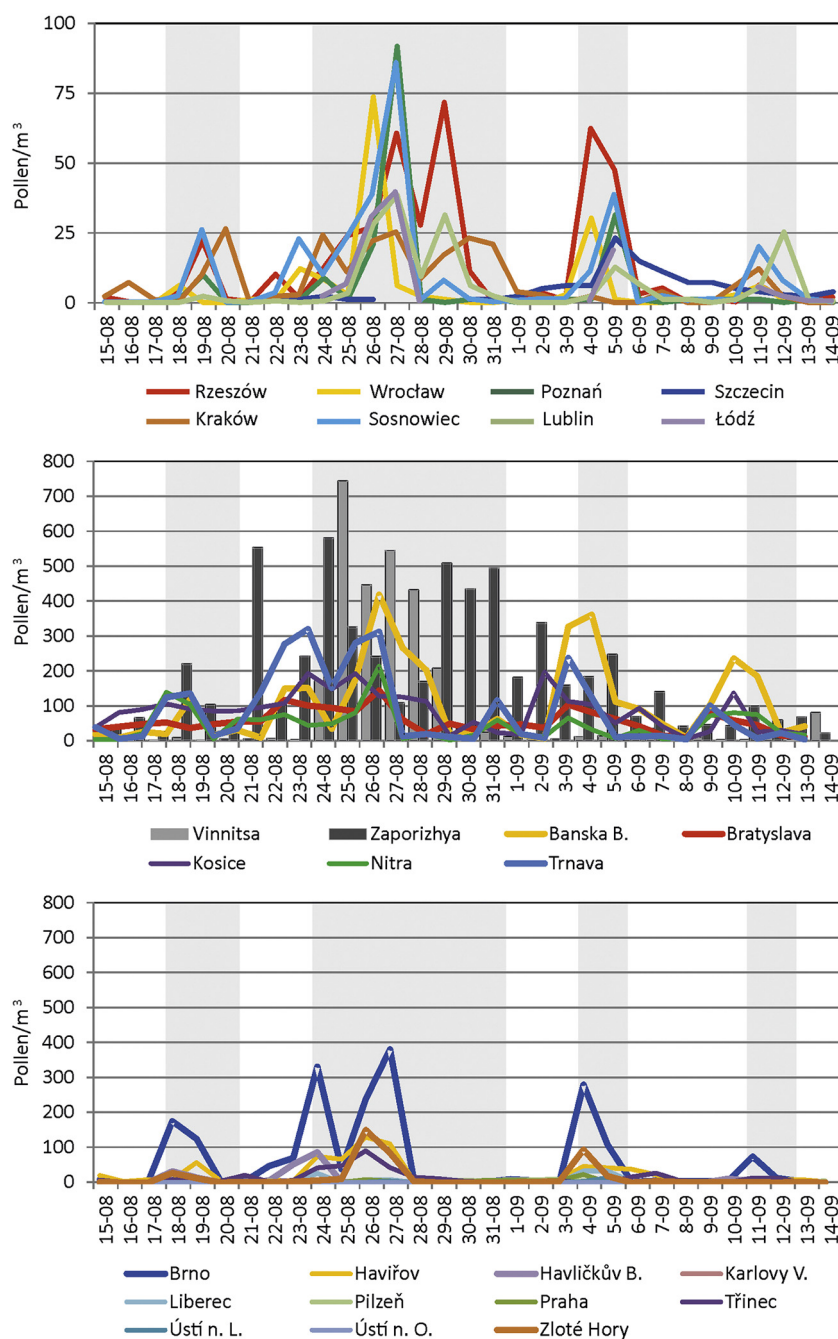


Fig. 6. Daily *Ambrosia* pollen concentrations at selected sites in Poland, Ukraine, Slovakia and the Czech Republic from 15 August to 14 September 2011.

In Poland annual sums of ragweed pollen grains are much lower than in southern Europe and in Ukraine (Puc, 2004; Piotrowska and Weryszko-Chmielewska, 2006; Stępańska et al., 2008; Kasprzyk et al., 2011), and the intermittent character of the ragweed pollen occurrence is characterized by a great variability of annual sums, similarly as it is observed in adjacent countries. Studies performed by Obtułowicz et al. (1995) in Poland, revealed that 42% of patients suffering from pollen allergy did not show allergy symptoms during the *Ambrosia* pollen season although they were sensitized to *Ambrosia* allergens. However, this could be changed when pollen concentrations increase e.g. because of the influx of air masses bearing ragweed pollen.

Over studied years *Ambrosia* pollen concentrations at sites in northern and central parts of the country were lower compared to southern sites (Fig. 3), where higher concentrations could result from the long distance pollen transport mainly from the southerly, but also from the

easterly directions. In cases related to the inflow of polar continental or tropical air masses into Poland the probability of such incidents was high. Stach et al. (2007) observed that pollen concentrations ≥ 20 Pollen/ m^3 in Poznań occurred with wind from southerly or easterly directions, which suggested the pollen transport from neighbouring areas more populated with *Ambrosia*. Grewling et al. (2019) found that *Ambrosia* pollen and fungal spores are often transported with mineral dust from the Sahara desert over the Pannonian Plain to the north (Poznań). The high ragweed pollen episodes presented by Grewling et al. (2019) for Poznań in 2005, 2006 and 2011 are confirmed by the present study for eight sites in Poland, which differ in pollen concentrations. The easterly direction identifies Ukraine as neighbouring source areas of ragweed pollen incoming to Poland (Puc, 2004; Chłopek and Tokarska-Guzik, 2006; Piotrowska and Weryszko-Chmielewska, 2006; Kasprzyk et al., 2011; Bilińska et al., 2017; Stępańska et al., 2017).

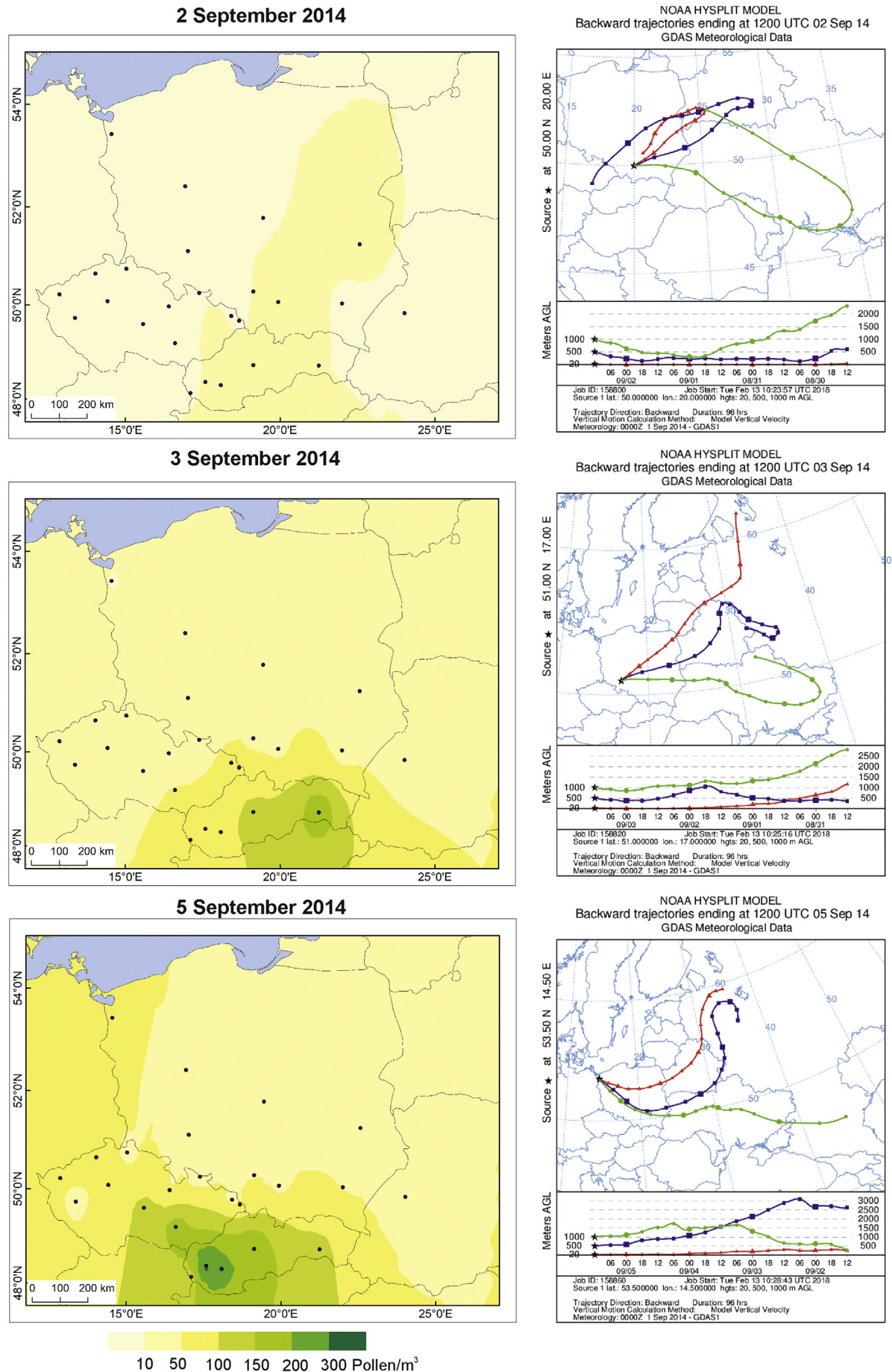


Fig. 7. A 4 day backward trajectory of air particles and daily *Ambrosia* pollen concentrations over Central Europe on 2, 3 and 5 September 2014.

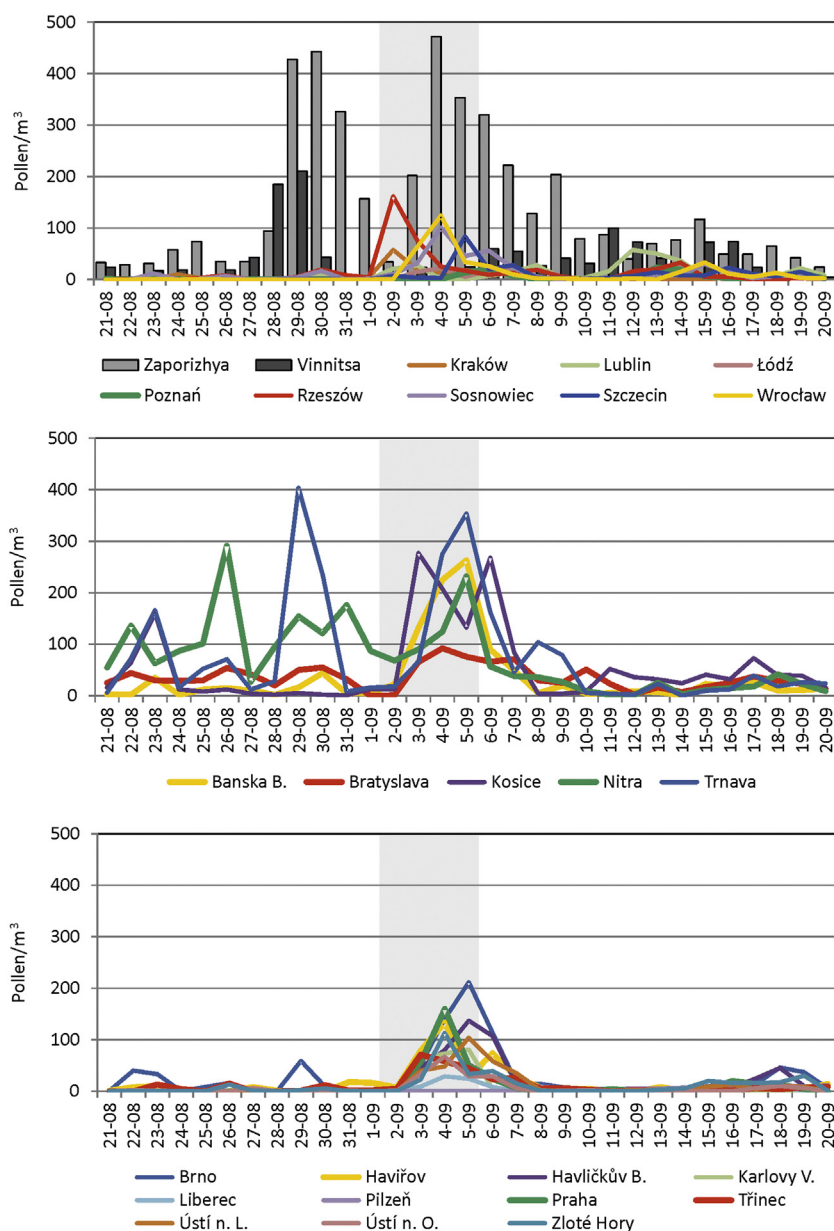


Fig. 8. Daily *Ambrosia* pollen concentrations at selected sites in Poland, Ukraine, Slovakia and the Czech Republic from 21 August to 20 September 2014.

Our hypothesis discussed in the previous work (Stępańska et al., 2017), regarding the long distance pollen transport, is confirmed in the present study on the basis of pollen data in Poland and in co-operating, neighbouring countries, and figured out backward trajectories. Synoptic maps presented in this paper and backward trajectory analyses clearly illustrate the sites outside Poland where pollen concentrations are high, and show the direction of air masses advection into Poland in a given day (Figs. 5, 7, 9). We did not include 2004 to the present work because there are not backward trajectories GDAS1 for 2004 on the website (<http://www.arl.noaa.gov>), but on the basis of reanalysis and *Calendar of synoptic situation* by Niedźwiedz (2019) it could be supposed, that then *Ambrosia* pollen arrived at Poland from the southerly direction. Our findings agree with results obtained in 2011 by Šikoparija et al. (2013) who reported the air masses advection bearing ragweed pollen in an adequate synoptic situation from the Pannonian Plain to Poznań (northwestern Poland). Therefore, Slovakia and the Czech Republic, from where pollen inflows into Poland, are only the “transit countries”. The inventory maps published by Skjøth et al. (2019) showed that areas with the highest ragweed abundances are

found south of Poland, in the Pannonian Plain (Slovakia, Hungary, Romania, the Balkan countries and Ukraine). Poland was classified as “areas with limited invasion and mainly in the urban zone” according to the land cover classes within the Corine Land Cover (CLC) classification.

In 2011, in the final report of the EU project “Assessing and controlling the spread and the effects of common ragweed in Europe”, the detailed maps on the spread of *A. artemisiifolia* from 1900 to 2011 in Europe are presented (Bullock, 2011). Generally, in Poland the highest density of ragweed sites is detected in the southern part of the country, in the vicinity of the Morawy Gate and in the eastern regions.

Considering all studied years and taking into account the average percentage of days with high pollen concentrations, the highest pollen value in Poland was recorded in 2014. Then air masses bearing *Ambrosia* pollen were translocated from the easterly direction consecutively to Wrocław on 3 September after passing the Rzeszów area on 2 September and to Poznań and Szczecin on 5 September. Pollen data obtained from Ukraine informed about high pollen concentrations in eastern Ukraine at the end of August. The high pollen concentrations in 2014

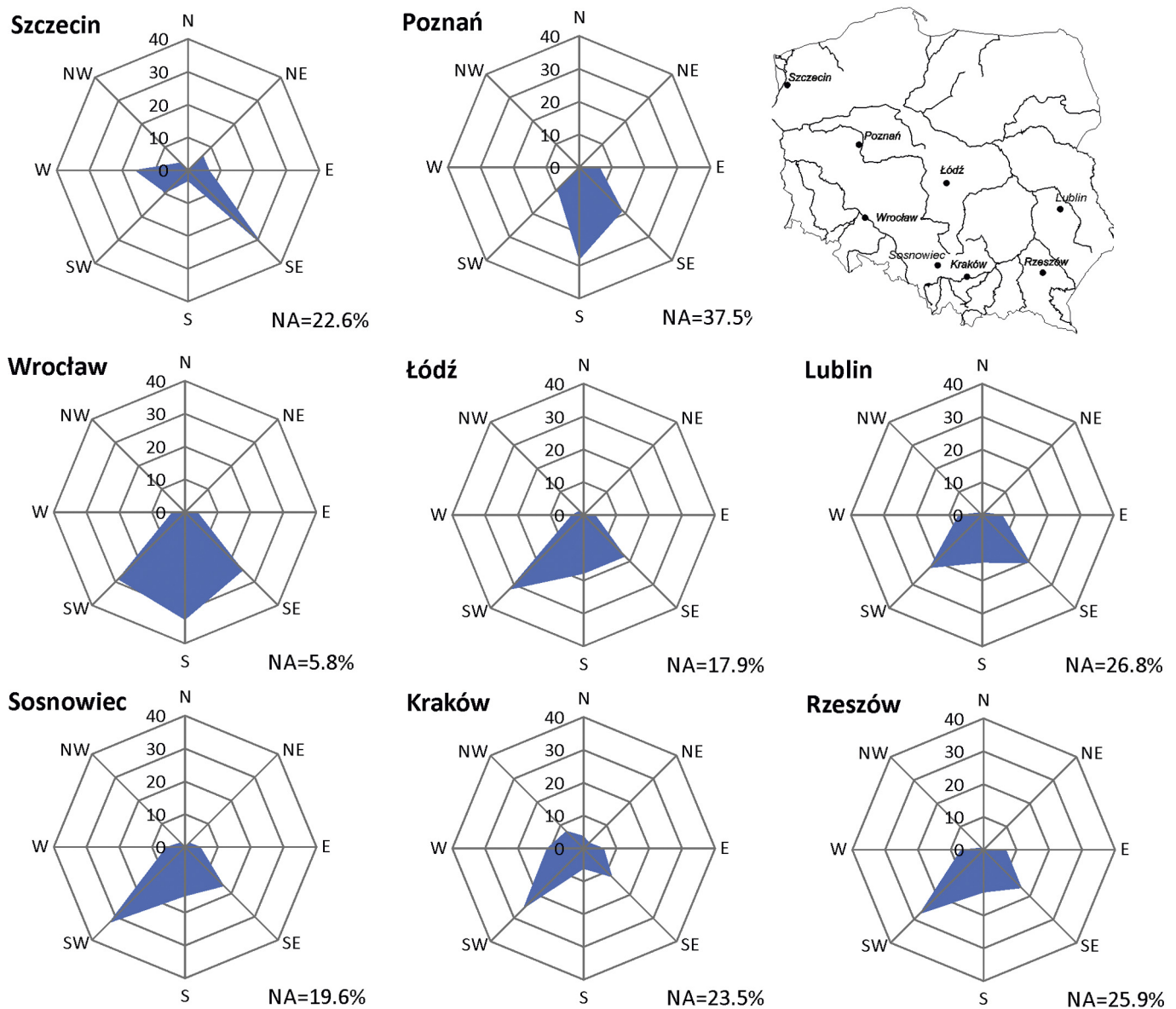


Fig. 9. Frequency (%) of directions of air masses advection in days with high *Ambrosia* pollen concentrations in Poland in 2003–2017 (NA – days with no advection situations; usually high pressure center)

were recorded mainly in Wrocław, Rzeszów and Lublin. Our findings agree with the report performed by Bilińska et al. (2017) who noted the high pollen concentration episode in Wrocław in 2014 being the consequence of the eastern inflow.

The direction of the air masses influx into Poland indicates neighbouring areas from which the air masses could reach studied sites in a given day. However, it could not be identified with wind, particularly in the lower layer of air, of which direction could be somewhat different than that one in the higher layers of air. The wind direction could be disturbed by landform changes or high buildings. However, the direction of the air masses inflow is not related to local modifications of the air-flow, but rather to translocation of air masses in higher atmosphere layers. According to Sofiev et al. (2013) the large-scale distribution of atmospheric components is monitored by synoptic-, continental-, or hemispheric- scale meteorological situations. Šikoparija et al. (2017) stressed, that few significant trends in the magnitude and frequency of atmospheric *Ambrosia* pollen reflect the strong variations in pollen sources. External factors, such as the introduction of control measures or herbivorous that target the plant, result in a significant decrease in the pollen load, while expansion in the source size or a

shortening of the distance from the source to the studied site are responsible for the increase in the pollen concentrations. The distinct decrease in ragweed pollen concentrations in Italy (Milan area) caused by the introduction of ragweed leaf beetle *Ophraella communa* reported Bonini et al. (2016). In no advection situations, there is no clear air masses direction but it does not mean that there is no air movement. There is possible the occurrence of convection, turbulence and air warming throughout the day which result in wind from different directions. High *Ambrosia* pollen concentration in no advection situation could originate from local sources and redeposition.

On the basis of performed analyses we can state that in 44% of days with high pollen concentrations in southern Poland, pollen grains were transported from South or South-West i.e. through the Czech Republic and Slovakia, and in about 6% of such days from East, from Ukraine. For sites located in central Poland these values were similar, 44% and 5% respectively. In northern Poland high pollen concentrations were accompanied by more differentiated directions of air masses advection, because besides the pollen transport from the Czech Republic and Slovakia (about 25%) and from Ukraine (about 10%), there were days with advection from West (Szczecin - 16%). The frequency of air masses

directions on days with concentrations ≥ 10 Pollen/m³ indicates the percentage of such days occurring when air masses come from a given direction (Fig. 9). Sometimes high *Ambrosia* pollen concentrations in Kraków were found when air masses approached the city from the northerly direction (Fig. 9). It is possible, when the air masses from the southerly direction after passing over the Carpathian Mountains are forced to turn back because of the geomorphology of the area or pollen might originate from redeposition. The low *Ambrosia* pollen concentration in Kraków, while pollen concentrations at adjoining sites in Sosnowiec, Rzeszów and Lublin were high, e.g. in 2004–2007 (Table 1), could result from a geographic position of Kraków, lying about 100 km away from the high range of the Tatra Mountains (up to 2655 m a.s.l.), which could be an obstacle for the free air-flow. The transport of air masses bringing *Ambrosia* pollen from southern Europe could be limited by a mountainous region which is a factor determining the *Ambrosia* pollen distribution. It agrees with Prank et al. (2013) who reported that natural mountainous barriers for pollen spread reduce *Ambrosia* pollen concentrations in northern and western parts of Europe. According to Smith et al. (2008) the transport of pollen over the Carpathian Mountains depends not only on the height of mountains but on the Planetary Boundary Layer (PBL) height as well. If mountains are low and PBL is higher than mountains, then the transport over mountains is possible. However, air masses could be translocated through depressions of the Morawy Gate and Dukielska Pass (a few hundred metres high) reaching Sosnowiec, Rzeszów and going further to the north (Šikoparija et al., 2013; Grewling et al., 2019). Sometimes *Ambrosia* pollen could fall down in Kraków but it depends on local weather conditions (precipitation, convection, wind speed and direction, local sources of pollen).

5. Conclusions

A 15 year study on *Ambrosia* pollen occurrence in Poland showed lower pollen concentrations in the northern and central parts of Poland (Szczecin, Poznań, Łódź, Wrocław) in contrast to higher concentrations in southern part (Sosnowiec, Rzeszów, Lublin). In view of our observation high pollen concentrations occur frequently when air masses arrive at Poland from the prevailing southerly directions (S, SE, SW, 44%), from Slovakia and the Czech Republic, and in no advection situation, usually associated with high pressure center (25%). The analysis of backward trajectories has shown, that the highest pollen concentrations in Poland were noted in 2014, when the pollen transport from the east (Ukraine) dominated (6%). The lower *Ambrosia* pollen concentrations in selected years in Kraków could result from a specific position of the city, situated near the high mountain areas limiting the long distance transport of air masses with pollen from southern Europe.

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CRediT authorship contribution statement

Danuta Stępańska: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Dorota Myszkowska:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Katarzyna Piotrowicz:** Formal analysis, Methodology, Validation, Visualization, Writing - review & editing. **Katarzyna Kluska:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Kazimiera Chłopek:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Łukasz Grewling:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Janka**

Lafférsová: Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Barbara Majkowska-Wojciechowska:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Małgorzata Malkiewicz:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Krystyna Piotrowska-Weryszko:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Małgorzata Puc:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Victoria Rodinkova:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Ondřej Rybníček:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Jana Ščevková:** Data curation, Investigation, Resources, Visualization, Writing - review & editing. **Kateryna Voloshchuk:** Data curation, Investigation, Resources, Visualization, Writing - review & editing.

Declaration of competing interest

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

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