

# The occurrence of *Ambrosia* pollen in Rzeszów, Kraków and Poznań, Poland: investigation of trends and possible transport of *Ambrosia* pollen from Ukraine

Idalia Kasprzyk · Dorota Myszkowska ·  
Łukasz Grewling · Alicja Stach · Branko Šikoparija ·  
Carsten Ambelas Skjøth · Matt Smith

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**Abstract** Previous studies have shown that ragweed pollen arrives in Poland from sources in the south, in Slovakia, the Czech Republic, Hungary and Austria. It is likely that ragweed pollen also arrives from sources in the southeast (e.g. Ukraine). This hypothesis was investigated using 13 years of pollen data and back-trajectory analysis. *Ambrosia* pollen data were collected at three sites in

Poland, Rzeszów, Kraków and Poznań. The amount of ragweed pollen recorded at Rzeszów was significantly higher than in Poznań and Kraków. This can be related to either a higher abundance of local populations of *Ambrosia* in south-east Poland or the proximity of Rzeszów to foreign sources of ragweed pollen. The combined results of pollen measurements and air mass trajectory calculations identified plumes of *Ambrosia* pollen that were recorded at Rzeszów, Kraków and Poznań on 4 and 5 September 1999 and 3 September 2002. These plumes arrived at the pollen-monitoring sites from an easterly direction, indicating sources of *Ambrosia* pollen in eastern Poland or Ukraine. This identifies Ukraine as a possible new source of ragweed pollen for Poland and therefore an important source area of *Ambrosia* pollen on the European Continent.

I. Kasprzyk (✉)

Department of Environmental Biology, University of Rzeszów,  
Rejtana 16c,  
Rzeszów 35-959, Poland  
e-mail: idalia@univ.rzeszow.pl

D. Myszkowska

Department of Clinical and Environmental Allergology,  
Jagiellonian University, Medical College,  
Śniadeckich 10,  
Kraków 31-531, Poland

Ł. Grewling · A. Stach

Laboratory of Aeropalynology, Adam Mickiewicz University,  
Umultowska 89,  
Poznań 61-614, Poland

B. Šikoparija

Department of Biology and Ecology, Laboratory for Palynology,  
University of Novi Sad,  
Trg Dositeja Obradovica 2,  
Novi Sad 21000, Serbia

C. Ambelas Skjøth

Department of Atmospheric Environment,  
National Environmental Research Institute, University of Aarhus,  
Frederiksborgvej 399, P.O. Box 358, Roskilde 4000, Denmark

M. Smith

National Pollen and Aerobiology Research Unit,  
University of Worcester,  
Worcester WR2 6AJ, UK

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## Introduction

The pollen grains of *Ambrosia* spp. (ragweed) contain very potent allergens that are known to cross-react with the allergens of *Artemisia* (Asero et al. 2006)—another member of the Asteraceae family. The threshold values provoking allergy symptoms differ in different countries. The threshold value is below 20 *Ambrosia* pollen grains per cubic metre in Austria (Jäger 2000), 13 pollen grains in France (Laaidi and Laaidi 1999), and 30 (Makra et al. 2005) or 50 (Juhász and Gallowich 1995) pollen grains in Hungary. In the United States, over 26% of the population is sensitive to *Ambrosia* pollen. In Europe, sensitisation is still increasing (Jäger 2000; Rybníček et al. 2000; Yankova et al. 2000;

Vitányi et al. 2003; Chrenová et al. 2009). In Hungary—one of the most ragweed-contaminated countries in Europe—approximately 60% of pollinosis sufferers are sensitive to *Ambrosia* pollen (Vitányi et al. 2003; Makra et al. 2005).

The genus *Ambrosia* contains about 40 species and several subspecies. Only one species, *A. maritima* L., is native to Europe (Vitányi et al. 2003; Tamaracaz et al. 2005). Other species found in Europe were introduced from the New World. The most frequently noted of these is *A. artemisiifolia* L. (= *Ambrosia elatior* L.) (short or common ragweed). Less common are *A. trifida* L. (= *A. aptera* DC.) (giant ragweed), *A. psilostachya* DC. (= *A. coronopifolia* Torr. & Gray) (perennial ragweed) and *A. tenuifolia* Spreng. (silver ragweed) (Laaidi and Laaidi 1999; Stępańska et al. 2002; Makra et al. 2005; Tamaracaz et al. 2005). The first records of *A. artemisiifolia* in Europe were in Croatia and Montenegro in the first half of the nineteenth century (de Visiani 1842). The plant was probably imported to Europe in ballast or seed lots. The distribution of ragweed increased after the First World War, but it was not considered invasive until the middle of the twentieth century. It favours sites of human activity and grows in ruderal habitats, along roads, railway embankments and fallow land. It is a noxious weed in agriculture (Vitányi et al. 2003).

In Europe, three main centres are infected by ragweed: (1) The Carpathian Basin/Pannonian Plain, primarily Hungary (Járai-Komlódi 2000; Juhász et al. 2004) but also parts of eastern Austria (Jäger 2000), Croatia (Juhász et al. 2004; Peternel et al. 2005), the Czech Republic (Rybníček et al. 2000), Romania (Juhász et al. 2004), Serbia (Juhász et al. 2004; Šikoparija et al. 2006), Slovakia (Makovcová et al. 1998), Slovenia (Juhász et al. 2004) and Ukraine (Mosyakin and Yavorska 2002); (2) the Rhône-Alpes region of France (Laaidi and Laaidi 1999; Laaidi et al. 2003); (3) Northern Italy, especially the northwest regions of Piedmont and Lombardy and the northeast regions of Veneto and Friuli-Venezia Giulia in northern Italy (Peternel et al. 2005; Cecchi et al. 2006). *Ambrosia* is expanding its distribution and has recently been noted in Germany (Brandes and Nietzsche 2006), Switzerland (Tamaracaz et al. 2005) and Poland (Stach et al. 2007; Stępańska et al. 2008).

Ragweed favours a warm continental climate, and dry, rich soils with neutral or slightly acid pH (Dahl et al. 1999; Stępańska et al. 2002; Peternel et al. 2005; Tamaracaz et al. 2005). Ragweed does not favour a cool maritime climate with high relative humidity (Comtois 1998; Dahl et al. 1999; Saar et al. 2000). Photoperiod and temperature are factors that determine the distribution of *Ambrosia*. It is a short-day plant and flowering starts in autumn. The average September temperature is the main parameter determining distribution (Reznik 2009). The northern limit of its range is near 50° N, and temperature also controls altitudinal

distribution (Allard 1945; Genton et al. 2005). As a result, *Ambrosia* is recorded only occasionally in northern European countries such as Sweden, and its pollen has yet to present a serious allergological problem (Dahl et al. 1999; Saar et al. 2000). In warmer southern Europe (Spain and southern Italy), the climate is unfavourable to short ragweed and giant ragweed because of long hot, dry summers involving excessive desiccation of air and soil (Allard 1945).

*Ambrosia artemisiifolia*, *A. psilostachya* and *A. trifida* have all been recorded in the flora of Poland. The former two taxa have the status of naturalised species, while *A. trifida* is regarded as sporadically introduced. *A. artemisiifolia* is most frequently noted (Chłopek and Tokarska-Guzik 2006). Ragweed has not been recorded at any sites in the flora of Rzeszów and its close vicinity. The three nearest (documented) sites of *A. artemisiifolia* were observed about 70 km east of Rzeszów—close to the border with Ukraine. One population occupies uncultivated land; the other two inhabit railway tracks (Tokarska-Guzik 2001; Nobis and Nobis 2006). In Kraków, several *Ambrosia* stands have been recorded near railway stations Płaszów and Bieżanów (Tokarska-Guzik 2001). *A. artemisiifolia* has been recorded in Poznań (Poland) in the past (Żukowski 1960; Jackowski 1993) but recent surveys have shown that these areas are no longer populated (Stach 2006).

Airborne ragweed pollen is frequently noted at all the aerobiological monitoring sites in Poland, but it is recorded only intermittently and concentrations are generally low. The highest annual totals of airborne *Ambrosia* pollen grains have been recorded in southern (Sosnowiec) and south-eastern (Lublin, Rzeszów) parts of the country (Chłopek and Dąbrowska 2006; Piotrowska and Weryszko-Chmielewska 2006).

Ragweed produces large quantities of pollen grains that are small (18–22 µm) and suitable for long-range transport (Dahl et al. 1999; Saar et al. 2000; Tamaracaz et al. 2005; Cecchi et al. 2006; Fumanal et al. 2007). Due to the limited distribution of *Ambrosia* in Poland it was assumed that the pollen of this plant recorded in the air of Poland originates primarily from allochthonous sources. Previous studies have shown that ragweed pollen arrives in Poland from sources in the south, in Slovakia, the Czech Republic, Hungary and Austria (Stach et al. 2007; Smith et al. 2008). It is likely that ragweed pollen arrives from other source regions such as Ukraine as suggested by previous authors (Stępańska et al. 2002). Ukraine contains large regions with climatic conditions that favour ragweed growth and as a result can potentially be an important source area of ragweed pollen for Europe via long-range transport to other regions such as Poland. The present study investigated this hypothesis using 13 years of pollen data from Poland and back-trajectory analysis.

## Materials and methods

### Ambrosia pollen data

*Ambrosia* pollen data were collected at three sites in Poland (Table 1) from 1997 to 2009 using volumetric spore traps of the Hirst design (Hirst 1952). Air is sucked into the trap at a rate of 10 l/min through a 2 mm×14 mm orifice. Behind the orifice, the air flows over a rotating drum (or microscope slide) that moves past the inlet at 2 mm/h and is covered with an adhesive coated, transparent plastic tape. Particles in the air impact on the tape, yielding time-stamped samples (Emberlin 2000). Following its removal from the trap, the tape is divided into segments corresponding to 24 h periods (48 mm in length) (Piotrowska and Weryszko-Chmielewska 2006). Each segment is mounted between a glass slide and cover slip using a mixture that usually contains gelatine, glycerine, phenol, distilled water and basic fuchsine (Laaidi et al. 2003). The samples are then examined by light microscopy. Two different counting methods were employed in this study: (1) in Rzeszów (1997–2009) and Poznań (1997–1999) a method similar to that described by Stach (2000) was used, whereby pollen grains were counted along 12 latitudinal transects, each corresponding to a 2-h interval (Kasprzyk 2008); (2) in Kraków (1997–2009) and Poznań (2000–2009) a technique similar to the method described by the Spanish Aerobiological Network (REA; Galán et al. 2007) was used, where slides were examined along 4 longitudinal transects divided into 2 mm intervals (2 mm=1 h). It should be noted that *Ambrosia* pollen data from 2007 and 2008 in Rzeszów were not available for analysis. The use of two different counting methods meant that it was necessary to transform hourly counts into 2-hourly counts so that a direct comparison could be made between sites. Daily average (0000 to 2400 hours) *Ambrosia* pollen counts and diurnal variations (2-h counts) are expressed as grains/m<sup>3</sup>.

### Climate

Poland is characterised by a Continental climate. Rzeszów and Kraków are situated in the Upper Vistula Basin—a temperate dry region. According to Niedźwiedź (1981,

2004) and Niedźwiedź and Obrębska-Starkłowa (1991), transformed polar-maritime air masses influence weather in this region. Winds are mainly from the west (SW, W and NW). Poznań is also located in an area of western circulation and, as a result, winds from the West and southwest predominate.

In Rzeszów, mean January and July temperature are  $-2.1^{\circ}\text{C}$  and  $19.1^{\circ}\text{C}$  respectively, and annual precipitation is 712 mm (mean data for 1997–2005). In the Rzeszów region, maximum and minimum precipitation occurs in July (mean 80 mm) and February (mean 27–50 mm), respectively (Brzeźniak 2007).

In Kraków, the mean January and July temperature are  $-2.5^{\circ}\text{C}$  and  $18.2^{\circ}\text{C}$ , respectively, and the annual precipitation ranges from 700 to 750 mm (Niedźwiedź and Obrębska-Starkłowa 1991; Matuszko 2007). Mean January and July temperatures in Poznań are  $-1.4^{\circ}\text{C}$  and  $19.2^{\circ}\text{C}$ , respectively, and mean annual precipitation is approximately 500 mm (Woś 1994; Stach 2000).

### Statistical analysis

Statistical analyses were performed on daily average *Ambrosia* pollen counts recorded in three periods during 1997–2009: (1) 1 August–30 September [VIII–IX]; (2) 1 August–15 October [VIII–15.X]; (3) 1 August–31 October [VII–X]. The period [VIII–IX] was selected because in Poland the maximum *Ambrosia* pollen concentrations are recorded in August and September (Kasprzyk 2008; Stepalska et al. 2008). However, *Ambrosia* pollen grains can also be observed from August to the first half of October [VIII–15.X] or for longer periods from July until the end of October [VII–X]. A screening test was used to select the statistical methods used in this paper. The screening test used was the Shapiro-Wilk (SW) test for normality. The SW test shows that the pollen data were not distributed normally and so non-parametric statistics were used. Variations in daily average *Ambrosia* pollen concentrations and seasonal pollen index (SPI) values in Rzeszów, Kraków and Poznań were identified using Friedman test and Nemenyi's procedure (multiple pairwise comparisons involving  $K$  group means). Taking into account the fact that there are  $k(k-1)/2$  possible comparisons, the correction of the significance level proposed by Bonferroni was applied

**Table 1** Pollen-monitoring sites used in this study

Site	Latitude		Longitude		Height above sea level (m)	Height of trap above ground level (m)	Number of years in study ( $n$ )
Poznań	52°	24' N	16°	53' E	86	33	13
Kraków	50°	04' N	19°	58' E	206	20	13
Rzeszów	50°	01' N	22°	02' E	202	12	11

(XLSTAT 2010). The relationship between daily average ragweed pollen counts recorded at the different stations was investigated using Spearman's rank non-parametric correlation analysis. The hypothesis was tested with  $P < 0.05$ , 0.01 and 0.001. Simple linear regression analysis was carried out in order to investigate trends over time. The following statistics are presented: the slope of the regression, standard error of the slope (SE), coefficient of determination ( $R^2$ ) and the probability level ( $P$ ). The calculations were carried out using statistical software packages the STATISTICA program version 8.0 and XLSTAT (2010).

#### Back-trajectory analysis

Back-trajectories indicate possible source areas and were calculated at the National Environmental Research Institute (NERI) in Denmark, following the methodology described by Stach et al. (2007). The back-trajectories were run at 6-hourly intervals throughout the study periods. Each back-trajectory was run for 4 days with 6-hourly steps. All times are presented as Central European Summer Time (UTC + 2).

#### *Ambrosia* pollen episodes tested for long-distance transport

The rationale for selecting episodes for further investigating using back-trajectory analysis is based on the work by Bianchi et al. (1959) and Ogden et al. (1969). The authors described how *Ambrosia* pollen form a local source peak in the morning (between about 0630 hours and midday). On the other hand, *Ambrosia* pollen recorded at night or in the early morning, before the local plants commence flowering, suggests that these pollen grains were released the previous day (or preceding days) and arrived via long-range transport. Such peaks in concentrations recorded in the night or early morning may be related to night-time cooling, which would deposit pollen grains that had been kept airborne during the day by convection (Faegri and Iversen 1992). This justification for selecting episodes for analysis was based on previous work by the authors, which have shown how back-trajectories in combination with measured pollen concentrations can be used to track plumes of *Ambrosia* that progress from source areas into countries such as Poland (Smith et al. 2008) or Macedonia (Šikoparija et al. 2009). Taking into account this description of *Ambrosia* pollen release, two ragweed pollen episodes were chosen for analysis. These episodes identified using the results of statistical analysis carried out on daily average and annual *Ambrosia* pollen counts were characterised by unusually high daily average ragweed pollen concentrations and *Ambrosia* pollen recorded at night or in the early morning.

## Results

### Analysis of pollen seasons

#### *Annual totals and daily pollen counts*

Annual sums of *Ambrosia* pollen grains (SPI) varied considerably between the three sites. The highest daily counts were recorded in 1999 and occurred almost on the same day (3, 4 and 5 September 1999) in Kraków, Rzeszów and Poznań, respectively. The years 1999, 2002 and 2005 also recorded daily average *Ambrosia* pollen counts  $>20$  grains/m<sup>3</sup> at all three sites (Table 2).

Spearman correlation analysis carried out on daily average *Ambrosia* pollen counts recorded in three periods during 1997–2009 (Table 3) shows that the strongest relationship between the daily *Ambrosia* pollen counts recorded at all three sites (Rzeszów, Kraków and Poznań) occurred in 1999, 2002 and 2005. The strongest synchronization in pollen seasons was between Rzeszów and Kraków in 2002. Relationships between pollen seasons were weakest for the period of August–October [VII–X], and were often not statistically significant (Table 3).

There were significant differences in the magnitude of daily average *Ambrosia* pollen counts recorded at these three sites during the three years mentioned (Table 4). Comparison of annual totals of ragweed pollen using the Friedman test showed that the SPI recorded at three sites differed significantly ( $P < 0.05$ , data not shown). The Nemenyis procedure also revealed significant differences ( $P < 0.05$ ) between the SPI noted at Rzeszów and the SPI recorded at Kraków and Poznań, but not between the SPI at Kraków and Poznań (Table 5). The highest *Ambrosia* SPI was recorded at Rzeszów and the lowest number of *Ambrosia* pollen grains recorded annually was at Poznań (Table 6). The number of days when the ragweed pollen counts exceeded 20 grains/m<sup>3</sup> was also highest in Rzeszów (Table 2).

#### *Trends in total yearly sum*

No significant trends were found in the amount of *Ambrosia* pollen recorded annually at Rzeszów, Poznań and Kraków during 1997–2009. However, in Kraków a slight upward trend was recorded and opposite tendencies were described in Poznań and Rzeszów (Table 6).

#### Back-trajectory analysis on 4 and 5 September 1999

Distinct peaks in daily *Ambrosia* pollen concentrations occurred at Rzeszów, Kraków and Poznań on 4 and 5 September 1999 (Table 7). Several fronts were located over the study area on 1 September, which were replaced by

**Table 2** Maximum daily *Ambrosia* pollen concentrations (grains/m<sup>3</sup>), day of maximum daily pollen concentrations (day from 1 January) and number of days with concentrations above 20 pollen grains/m<sup>3</sup> recorded in Rzeszów, Kraków and Poznań during 1997–2009. CV Coefficient of variation

Year	Maximum daily pollen concentrations (grains/m <sup>3</sup> )			Day of maximum daily average <i>Ambrosia</i> pollen concentration (day from 1 January)			Number of days >20 <i>Ambrosia</i> pollen grains/m <sup>3</sup> daily average		
	Rzeszów	Kraków	Poznań	Rzeszów	Kraków	Poznań	Rzeszów	Kraków	Poznań
1997	34	6	44	235	237	238	2	0	3
1998	125	47	12	253	255	249	4	1	0
1999	319	85	109	247	246	248	6	5	4
2000	86	14	12	234	232	241	7	0	0
2001	98	34	41	247	229	243	2	1	1
2002	98	39	92	248	247	240	6	1	4
2003	55	23	9	255	241	241	5	1	0
2004	42	31	6	243	243	255	3	1	0
2005	59	29	53	253	237	250	5	1	3
2006	64	14	51	237	268	257	3	0	4
2007		21	48		234	234		1	1
2008		70	22		249	245		7	1
2009	98	50	16	246	253	253	4	3	0
Mean	98.0	35.6	39.6	245.3	243.9	245.7	4.3	1.7	1.6
SD	78.4	22.8	32.2	7.3	10.8	7.0	1.7	2.1	1.7
CV(%)	80.0	63.9	81.2	3.0	4.4	2.8	39.3	123.9	105.8

high pressure over Northern Germany (~1,025 hPa) on 2 September. During this period, the approaching air masses gradually veered from the Northwest to the East. Daily average *Ambrosia* pollen counts >20 grains/m<sup>3</sup> were recorded at Rzeszów and Kraków from 3 to 7 September,

at Poznań from 4 to 6 September. This corresponded to a period when an area of high-pressure in the region of ~1,033–1,030 hPa remained over European Russia, and low-pressure centres were located to the north of the British Isles and Scandinavia. The air masses continued to veer

**Table 3** Spearman correlation coefficients between daily average *Ambrosia* pollen concentrations recorded in Rzeszów, Kraków and Poznań in three periods during 1997–2009: (1) 1 August–30 September [VIII–IX]; (2) 1 August–15 October [VIII–15.X]; (3) 1 August–31 October [VIII–X];

Year	Rzeszów-Kraków			Kraków-Poznań			Rzeszów-Poznań		
	VIII-IX	VIII-15.X	VIII-X	VIII-IX	VIII-15.X	VIII-X	VIII-IX	VIII-15.X	VIII-X
1997	0.278*	0.290**	0.279*	0.243*	0.281**	NS	0.431***	0.424***	0.435***
1998	0.384***	0.409***	0.335**	0.542***	0.544***	0.537***	0.428***	0.441***	0.396**
1999	0.427***	0.433***	0.437***	0.580***	0.583***	0.593***	0.484***	0.495***	0.501***
2000	0.317**	0.344***	0.364**	NS	NS	NS	NS	NS	NS
2001	0.347**	0.436***	0.302*	0.314**	0.362***	0.340**	NS	0.211*	NS
2002	0.709***	0.715***	0.699***	0.608***	0.622***	0.582***	0.587***	0.602***	0.573***
2003	0.348**	0.415***	NS	0.248*	0.270**	NS	NS	NS	NS
2004	0.498***	0.495***	0.512***	NS	NS	NS	NS	NS	NS
2005	0.450***	0.519***	0.371**	0.237*	0.321**	NS	0.642***	0.669***	0.594***
2006	NS	NS	NS	0.382***	0.415***	0.317*	NS	NS	NS
2007				NS	0.214*	NS			
2008				0.447***	0.469***	0.412***			
2009	0.314**	0.362***	NS	0.388***	0.419***	0.337**	0.271*	0.315**	NS
1997–2009	0.303***	0.340***	0.305***	0.324***	0.308***	0.296***	0.287***	0.349***	0.295***

\*P<0.05 \*\*P<0.01 \*\*\*P<0.001, NS Non-significant



**Table 4** Multiple pairwise comparisons using Nemenyi's procedure between daily average *Ambrosia* pollen concentrations recorded in Rzeszów, Kraków and Poznań during 1997–2009

Year	period City	VIII-X			VIII-15X			VIII-IX		
		Rzeszów	Kraków	Poznań	Rzeszów	Kraków	Poznań	Rzeszów	Kraków	Poznań
1997	Rzeszów		NS	NS		NS	NS		NS	NS
	Kraków	NS		NS	NS		NS	NS		NS
1998	Rzeszów		*	*		NS	*		NS	NS
	Kraków	*		NS	NS		NS	NS		NS
1999	Rzeszów		*	NS		*	NS		*	NS
	Kraków	*		NS	*		NS	*		NS
2000	Rzeszów		*	NS		*	NS		*	NS
	Kraków	*		NS	*		NS	*		NS
2001	Rzeszów		NS	NS		NS	*		NS	*
	Kraków	NS		*	NS		*	NS		*
2002	Rzeszów		NS	*		NS	*		NS	*
	Kraków	NS		*	NS		*	NS		*
2003	Rzeszów		*	NS		*	NS		NS	*
	Kraków	*		*	*		*	NS		*
2004	Rzeszów		*	NS		*	NS		*	NS
	Kraków	*		*	*		*	*		*
2005	Rzeszów		NS	NS		NS	NS		NS	*
	Kraków	NS		NS	NS		NS	NS		NS
2006	Rzeszów		NS	NS		NS	NS		NS	NS
	Kraków	NS		NS	NS		NS	NS		NS
2009	Rzeszów		NS	NS		NS	NS		NS	NS
	Kraków	NS		NS	NS		NS	NS		NS

\*  $P < 0.05$  (Bonferroni corrected significance level: 0.0167), NS non significant

slowly to the South and West. *Ambrosia* pollen counts at the three sites in Poland decreased on 7 and 8 September when air masses approached from a more southwesterly direction. Back-trajectory analysis shows that air masses approaching Rzeszów, Kraków and Poznań passed over eastern Poland and Ukraine on 4 and 5 September 1999 (Fig. 1a). The diurnal variations for the three sites (Fig. 1b) show that there was a night-time peak at Poznań between 2200 on 4 September and 0200 on 5 September (the highest bi-hourly concentration was 428 ragweed pollen grains/m<sup>3</sup> recorded at 0200 hours on 5 September). The plume can be tracked backwards as it passes over Kraków at around mid-afternoon (between 1400 and 1600 hours) and Rzeszów during mid-morning (highest bi-hourly concentration at

Rzeszów was 1,080 ragweed pollen grains/m<sup>3</sup> recorded at 1000 hours on 4 September 1999.

#### Back-trajectory analysis on the 3 September 2002

*Ambrosia* pollen concentrations at the sites examined in Poland from 1 to 2 September 2002 were generally low (<10 grains/m<sup>3</sup>), except at Rzeszów where daily average *Ambrosia* pollen counts >20 grains/m<sup>3</sup> were recorded on 1 September 2002. Daily average *Ambrosia* pollen counts approaching or >20 grains/m<sup>3</sup> were recorded at Rzeszów from 3 to 6 September, at Poznań from 3 to 5 September, and at Kraków on 4 September (Table 7). The synoptic situation in this period was characterised by a series of low-

**Table 5** Spearman rank correlation test and Nemenyi's procedure applied to total annual *Ambrosia* pollen counts (SPI) recorded in Rzeszów, Kraków and Poznań during 1997–2009

	Spearman correlation test			Nemenyi's procedure		
	Rzeszów	Kraków	Poznań	Rzeszów	Kraków	Poznań
Rzeszów		0.127	0.246		*	*
Kraków			0.110			NS
Poznań						

\*  $P < 0.05$ , NS non significant

**Table 6** Trends in total annual *Ambrosia* pollen counts (SPI) recorded in Rzeszów, Kraków and Poznań during 1997–2009

	SPI		
	Rzeszów	Kraków	Poznań
Mean	378.0	170.5	126.5
SD	212.6	122.0	109.5
CV(%)	56.3	71.6	86.5
slope	-19.0	12.0	-7.5
SE	18.3	8.7	8.2
$R^2$	0.1	0.1	0.1
$P$	0.3	0.2	0.4

pressure systems (~965–986 hPa) that passed to the north of the British Isles on their passage from the North Atlantic toward Svalbard (North of mainland Scandinavia) and Arctic Russia. Corresponding high-pressure areas were located in the vicinity of Continental Europe (~1,017–1,032 hPa). In the morning of 1 September 2002, air masses approached the pollen-monitoring sites from a southerly direction before veering to the north later in the day. The air masses continued to veer throughout the episode, first approaching from the North to Northeast (2 September), then from the Northeast to South (3–5 September) and finally from the South to West (6–7 September). Back-trajectory analysis shows that possible sources of *Ambrosia* pollen on 3 September 2002 included eastern Poland and Ukraine (Fig. 2a). The highest bi-hourly ragweed pollen concentration recorded at Poznań on 3 September 2002 was 134 grains/m<sup>3</sup> at 1600 hours (Fig. 2b). Similar to the episode on 4 and 5 September 1999, the plume of *Ambrosia* pollen can be followed as it passed Kraków and Rzeszów. The peak is not as noticeable at Kraków; there was a small peak of 33 grains/m<sup>3</sup> at 1400 hours, which followed a larger peak of 58 grains/m<sup>3</sup> at 0600 hours. However, there was a larger bi-hourly peak of 130 ragweed pollen grains/m<sup>3</sup> recorded at Rzeszów at 1000 hours on 3 September 2002.

## Discussion

The ability of *Ambrosia* pollen grains to be transported long distances means that ragweed pollen from regions with abundant sources of *Ambrosia* can be responsible for high ragweed pollen concentrations in areas where the source plant is scarce or not even registered (Šikoparija et al. 2009). In areas considered to be centres of ragweed pollen production, such as France and Hungary, ragweed pollen is the most frequent cause of allergy symptoms during late

summer. In Poland, where most ragweed pollen is considered to be allochthonous, studies have shown that 42% of patients suffering from pollen allergy did not show symptoms of allergy during the *Ambrosia* pollen season although they were sensitised to *Ambrosia* allergens (Obtułowicz et al. 1995).

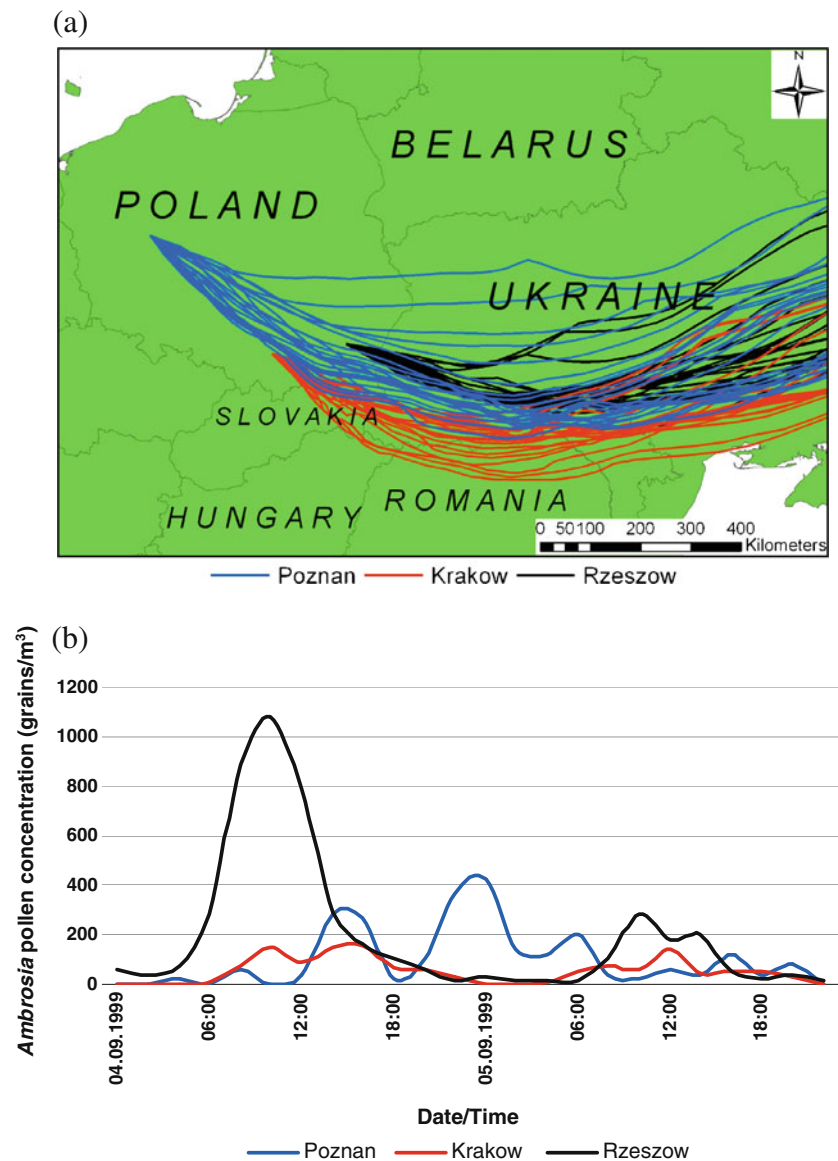
In order treatment to be effective, allergy patients need to be able to plan their medication in advance (Stern et al. 1997; Sabbah et al. 1999; Bousquet et al. 2001). This planning requires knowledge of atmospheric pollen concentrations several days before, and so reliable pollen forecasts are needed. Information about possible sources of pollen, including long-distance transport, would increase the accuracy of such forecasts (Skjøth et al. 2008). A number of studies, using a combination of *Ambrosia* pollen data and air mass trajectories, have contributed to the knowledge of potential source areas of ragweed in Central Europe and conditions that lead to regional scale or long-distance transport episodes (Cecchi et al. 2006, 2007; Stach et al. 2007; Smith et al. 2008; Šikoparija et al. 2009). The eventual aim of this work is to produce a numerical forecast for *Ambrosia* pollen.

An operational dispersion model for *Ambrosia* pollen would require several components, including an emission inventory and a phenological model capable of predicting flowering in the source area. Emission inventories of sources are rarely available for pollen (Skjøth et al. 2010), but when applied by a transport model the inventory can be used for analysing conditions needed for the long-distance

**Table 7** Daily average *Ambrosia* pollen counts (grains/m<sup>3</sup>) recorded at the three sites included in this study on 1–8 September 1999 and 1–8 September 2002

	Rzeszów	Kraków	Poznań
1 September 1999	1	0	0
2 September 1999	6	0	0
3 September 1999	101	86	15
4 September 1999	319	66	97
5 September 1999	80	42	109
6 September 1999	88	71	70
7 September 1999	30	26	15
8 September 1999	7	0	0
1 September 2002	60	8	2
2 September 2002	0	6	0
3 September 2002	36	17	38
4 September 2002	84	39	32
5 September 2002	98	10	37
6 September 2002	40	5	1
7 September 2002	12	3	0
8 September 2002	9	5	0

**Fig. 1** **a** Back-trajectory analysis for 4 and 5 September 1999 calculated at Rzeszów, Kraków and Poznań. **b** Bi-hourly *Ambrosia* pollen counts recorded at the three sites during the same period



transport of ragweed pollen (Šikoparija et al. 2009). Back-trajectories can therefore be used to discover sources of ragweed pollen for the inventory, as well as to identify specific episodes that can be used to calibrate the dispersion model. However, source-based dispersion models cannot be used unless the main source regions are adequately described. This is of high priority as emission inventories are generally considered to be among the biggest uncertainties in atmospheric transport models (Russell and Dennis 2000). As a result, studies that identify main source regions such as this one are important.

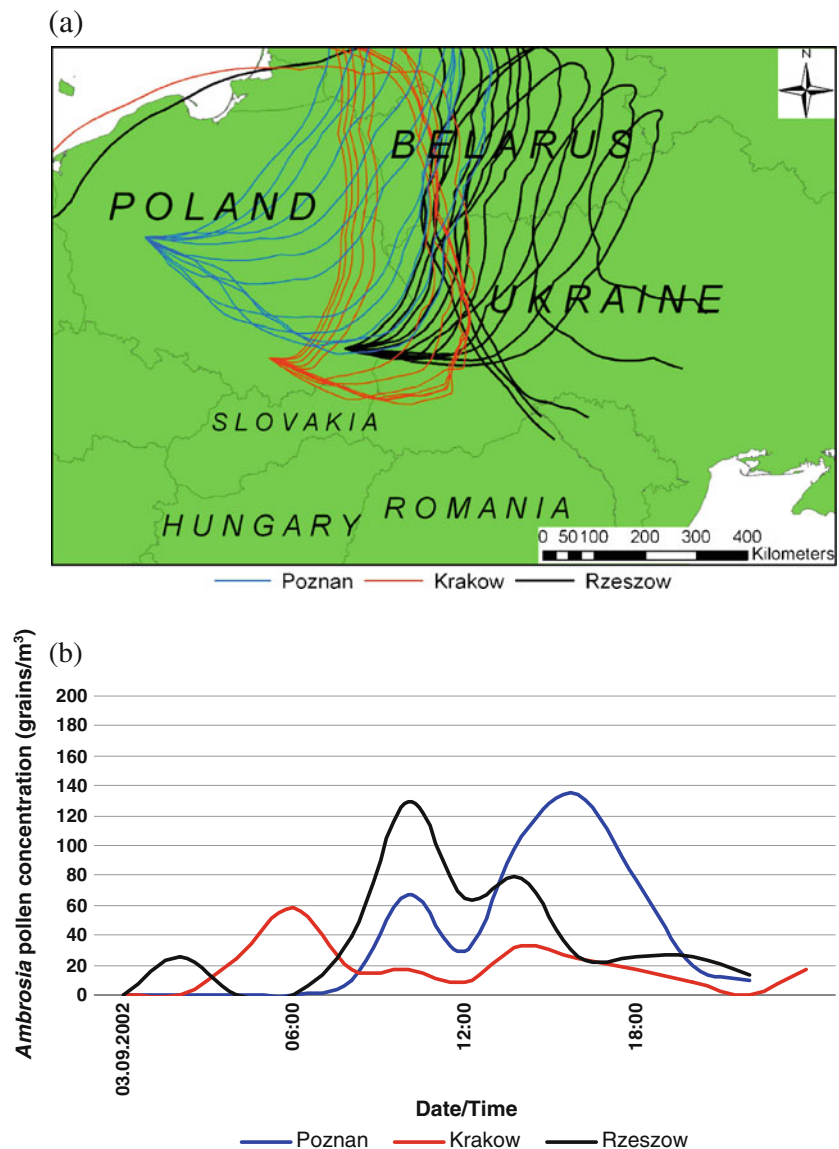
This study revealed that the amount of ragweed pollen in Rzeszów was significantly higher than in Poznań and Kraków. This can be related to both the higher abundance of local populations of *Ambrosia* in south-east Poland and

the proximity of Rzeszów to foreign sources of ragweed pollen. The intermittent character of ragweed pollen in Poland is expressed by the high variability of annual pollen sums and the lack of distinctly marked trends. Due to the scattered distribution of ragweed populations in Poland, the occurrence of *Ambrosia* pollen relies mainly on conditions being appropriate for long-range transport (Stach et al. 2007; Smith et al. 2008).

The results of statistical analysis show that there were three years (1999, 2002 and 2005) when a combination of significant correlations between daily average *Ambrosia* pollen counts, and daily average *Ambrosia* pollen counts >20 grains/m<sup>3</sup> was recorded at all three sites (Tables 2, 3). This suggests that high concentrations of pollen grains occurred in the air of Rzeszów, Kraków and Poznań almost at the same time. It is likely that



**Fig. 2** **a** Back-trajectory analysis for 3 September 2002 calculated at Rzeszów, Kraków and Poznań. **b** Bi-hourly *Ambrosia* pollen counts recorded at the three sites during the same period



this synchronisation of pollen seasons in different places was caused by transport of pollen from distant sources.

The *Ambrosia* pollen episode that occurred in 2005 has been well documented (Stach et al. 2007; Smith et al. 2008) and showed that air masses arrived in Poland predominantly from the Czech Republic, Slovakia and Hungary, passing mountain areas via the Morawy Gate and Low Beskid passes, identifying these countries as potential source areas. In this study, the combined results of pollen measurements and air mass trajectory calculations identified plumes of *Ambrosia* pollen that were recorded at Rzeszów, Kraków and Poznań on 4 and 5 September 1999 and 3 September 2002. These plumes arrived at the pollen-monitoring sites from an easterly direction and indicated that sources of *Ambrosia* pollen were present in either eastern Poland, in the region around Rzeszów, or Ukraine

Kasprzyk (2008) also evaluated the effect of weather conditions on daily *Ambrosia* pollen concentrations in Rzeszów from 3 to 5 September 1999. The author noted that the prevailing wind was from an East-North-East (3 September) or East-South-East (4 and 5 September) direction, and that the greatest number of pollen grains was recorded during the day, at about noon. This led the author to suggest that a midday maximum may indicate that the sources of pollen were not as far away as was previously supposed (Kasprzyk 2008). The results of the current study support this view, as the noon peak in ragweed pollen concentrations registered in Rzeszów during both episodes indicates that the pollen brought to Poland originated either from local Polish populations or Ukrainian populations situated close to the Polish border. In addition, it should be noted that ragweed pollen arriving at the Polish sites included

in this study could have travelled for a long time, even from regions situated further to the East (Fig. 1) and North (Fig. 2) in Ukraine. Such regional scale transport could augment ragweed pollen emitted from local sources around Rzeszów.

Back-trajectories calculated at the time of peak *Ambrosia* pollen concentration on 3 September 2002 at Poznań are similar to those presented by Stach et al. (2007). In this latter study, the authors described how the air masses passed over eastern Poland after traversing parts of Russia and Lithuania (Stach et al. 2007). However, back-trajectories calculated for Kraków and Rzeszów suggested that the *Ambrosia* pollen may have originated from territory further east. One reason for this contradiction might be related to the amount of uncertainty involved in calculating the path taken by a parcel of air. For example, the path of a single trajectory will differ depending on the release height of the parcel in the atmosphere. Furthermore, trajectory models are, in general, very sensitive to the quality and resolution of input data. It has been shown that changing input data from 150 km grid resolution and 6-h temporal resolution to 39 km grid resolution and 1-h temporal resolution, increased the accuracy significantly (Skjøth et al. 2002). As such, a single trajectory can be very uncertain, depending on the input data and the choice of the calculation method. One way of estimating the uncertainty of the trajectories is to use a matrix of several trajectories for single episodes, where trajectories start at different locations at some distance to each other. The spread between the trajectories is then an indicator of the accuracy of the reference trajectory. This trajectory matrix has been employed as a standard methodology for a number of studies (Smith et al. 2005, 2008; Skjøth et al. 2007, 2008; Stach et al. 2007), and in 2010 was adapted as a standard methodology in the on-line version of the HYSPLIT trajectory model (Draxler and Rolph 2010).

Two examples of regional scale transport are presented in this paper. If the plumes of *Ambrosia* pollen tracked on 4 and 5 September 1999 and 3 September 2002 did not originate from inside Poland, then it is likely that they came from Ukraine, where *Ambrosia psilostachya*, *A. artemisiifolia* and *A. trifida* occur in nearly all of the country (Mosyakin and Yavorska 2002; Protopopova et al. 2003; Grygorak et al. 2004). The total area of ragweed distribution in Ukraine now exceeds 10,000 km<sup>2</sup> and is still increasing (Reznik 2009). This identifies a possible new source of ragweed pollen for Poland as well as other European countries. Bearing in mind the fact that winds in the studied region are predominantly from the west and that studies have shown that the most ragweed pollen is transported from eastern and southern directions into Poland (Stach et al. 2007; Smith et al. 2008), we can suggest that western parts of Poland could be considered free of abundant ragweed populations and that the most potent sources of ragweed pollen recorded in Poland are situated in Ukraine and the Pannonian Plain.

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