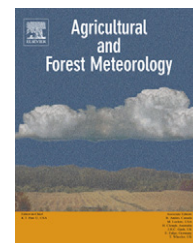


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Long-range transport of *Ambrosia* pollen to Poland

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ARTICLE INFO

Article history:

Received 15 June 2007

Received in revised form

22 February 2008

Accepted 11 April 2008

Keywords:

Aerobiology

Ragweed

Ambrosia

Back-trajectory analysis

Planetary Boundary Layer

ABSTRACT

The long-range transport of *Ambrosia* pollen to Poland is intermittent and mainly related to the passage of air masses over the Carpathian and Sudetes mountains. These episodes are associated with hot dry weather, a deep Planetary Boundary Layer (PBL) in the source areas and winds from the south. Such episodes can transport significant amounts of *Ambrosia* pollen into Poland.

The study investigates *Ambrosia* pollen episodes at eight sites in Poland during the period 7th–10th September 2005, by examining temporal variations in *Ambrosia* pollen and back-trajectories. PBL depths in the likely source areas were calculated with the Eta meteorological model and evaluated against the mountain heights.

Considerable amounts of *Ambrosia* pollen were recorded at several monitoring sites during the night or early in the morning of the investigated period. Trajectory analyses shows that the air masses arriving at the Polish sites predominantly came from the south, and were in the Czech Republic, Slovakia and Hungary the previous day indicating these countries as potential source areas.

We have shown the progress of *Ambrosia* plumes into Poland from the south of the country, probably from Slovakia and Hungary, and demonstrated how Lagrangian back-trajectory models and meteorological models can be used to identify possible transport mechanisms of *Ambrosia* pollen from potential source regions.

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1. Introduction

Pollen grains from the genus *Ambrosia* spp. (ragweed) are considered to be very potent aeroallergens. The threshold

value for clinical symptoms for ragweed pollen grains for the majority of sensitised patients is below 20 grains/m³ (Comtois, 1998; Jäger, 1998, 2000; Tamaracac et al., 2005). *Ambrosia* pollen appears to induce asthma about twice as often as other

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doi:10.1016/j.agrformet.2008.04.005

pollen, and there is significant cross-reactivity between ragweed species within the *Ambrosia* genus as well as between the major allergens of *Ambrosia* and *Artemisia* (Dahl et al., 1999; Jäger, 2000; White and Bernstein, 2003; Taramaracaz et al., 2005).

Ambrosia is present in the Czech Republic, Slovakia and Hungary (Járai-Komlódi, 2000; Laaidi et al., 2003; Puc, 2004; Makra et al., 2005; Peternel et al., 2005). In Hungary, the main *Ambrosia* pollen season is from July to October and the most *Ambrosia* pollen grains are present in the air during August and September (Makra et al., 2005), which is consistent with other countries in the region (Peternel et al., 2006). Daily average ragweed pollen counts of 2000 pollen grains/m³ have been experienced in Hungary, where annual sums of ragweed pollen can reach almost 20,000 grains (Járai-Komlódi, 2000; Makra et al., 2005).

Bianchi et al. (1959) showed that there is a definite diurnal periodicity in *Ambrosia artemisiifolia* flowering, with the extension and opening of the anthers occurring between 06:30 and 08:00, which correlated with a rise in temperature and reduction of relative humidity. The authors noted that the time required for the number of opened *A. artemisiifolia* flowers to reach its maximum for the day varied from 0.5 to 2 h, and described how the pollen falls in clusters from the flowers. These clusters adhere to foliage, from which the grains could be blown by the wind after separating (Bianchi et al., 1959). Peak concentrations of *Ambrosia* pollen have been reported from approximately 06:30 to around midday in field studies where the trap was located in the centre of plots of *Ambrosia* at a height of 0.1–0.5 m above the plants (Ogden et al., 1969). However, the time that the pollen is recorded will vary depending on the transport time (a product of distance and wind speed) from the source to the trap. For example, in Burgundy peak diurnal concentrations attributed to a local source were recorded between 09:00 and 13:00 at traps situated at a similar height above the ground to the traps used in this study (Laaidi and Laaidi, 1999). Conversely, *Ambrosia* pollen recorded at night or in the early morning, before the local plants commence flowering, suggests that the pollen grains were released the previous day (or preceding days) and arrived via long-range transport. It should also be noted that a peak in the night or early morning may be related to nighttime cooling that would deposit pollen grains that had been kept airborne during the day by convection (Faegri and Iversen, 1992).

Each ragweed plant produces millions of pollen grains that are small (18–22 µm) and suitable for long-range transport when conditions are favourable (Comtois, 1998; Dahl et al., 1999; Taramaracaz et al., 2005; Cecchi et al., 2006). Back-trajectory analysis has been used to study *Ambrosia* pollen episodes in a number of countries (Belmonte et al., 2000; Saar et al., 2000; Cecchi et al., 2006). In Poland, for instance, Stach et al. (2007) used back-trajectory analysis to examine *Ambrosia* pollen episodes at Poznań between 1995 and 2005. The analyses showed that plants of the genus *Ambrosia* spp. may be present locally because *Ambrosia* pollen that arrived in Poznań during the afternoon was brought by air masses that generally remained within the borders of Poland for 24 h or longer, but they also indicated that *Ambrosia* pollen grains that arrived in Poznań during night and early morning came via

long-range transport from air masses that passed over southern Poland, the Czech Republic, Slovakia and Hungary. *Ambrosia* pollen grains present in Poland can therefore be separated into two components: (1) locally emitted pollen and (2) long-range transport.

Daily variations in ragweed pollen concentrations are most affected by unstable atmospheric conditions (Taramaracaz et al., 2005). Such conditions are especially found during hot, dry, sunny days when the Planetary Boundary Layer (PBL) can reach depths of several thousand meters during the day and less than a few hundred meters during the night. Pollen grains that are released during hot sunny days may be transported up into the atmosphere and found throughout the PBL (Gregory, 1961; Raynor et al., 1974). In areas such as Hungary where *Ambrosia* is abundant, high amounts of ragweed pollen may follow the development of the PBL, which would result in high pollen concentrations more than 1000 m up in the atmosphere during day time. The border between southern Poland and the Czech Republic and Slovakia consists of the Carpathian and Sudetes mountains. Large areas of these mountain ranges are above 1000 m in height with peaks above 2000 m in the Central part of the Carpathians but there are also several passes that are only a few hundred meters high, such as the Morawy Gate between the Sudetes and the Carpathian Mountains and the Low Beskid between the East and West Carpathians (Fig. 1). Most of the mountain areas have a similar elevation to the PBL during the majority of the day. The mountain areas may therefore limit long-range transport from the South. It is also likely that episodes that combine deep PBLs of several thousand meters and southerly winds could result in long-range transport of *Ambrosia* pollen to Poland, where the highest amount of pollen grains will be transported over and around areas of high elevation. We have therefore formulated

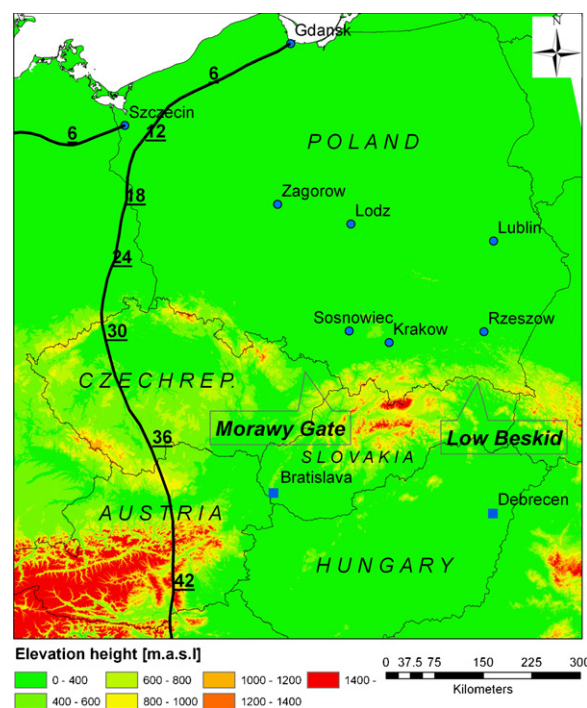


Fig. 1 – Back-trajectory analysis, start of run 14:00 on the 8th September 2005 from Gdansk and Szczecin.

the hypothesis that the long-range transport of *Ambrosia* pollen to Poland is intermittent and mainly related to the passage of air masses over the Carpathian and Sudetes mountains in the south. These episodes are associated with hot dry weather, deep PBLs in the source areas and winds from the south. Such episodes can transport significant amounts of *Ambrosia* pollen into Poland.

We will test the hypothesis by further examining the *Ambrosia* pollen episodes in 2005 that were previously studied by Stach et al. (2007) for the Poznań area, by using data from eight pollen-monitoring sites across the country. Trajectory calculations will be used to estimate transport path and possible source areas. The depth of PBLs will be calculated in the source areas. This will extend the work presented by Stach et al. (2007) and will show how long-range transport can affect *Ambrosia* pollen concentrations over a wide area.

2. Materials and methods

2.1. *Ambrosia* pollen data

Ambrosia pollen data were collected at eight sites in Poland (Table 1) by 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 to give a time related sample (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 fuchsin (Laaidi et al., 2003). The samples are then examined by light microscopy. Two different counting methods were employed in this study. Five of the sites (Szczecin, Zagorow, Lublin, Sosnowiec, and Krakow) used a technique similar to the method described by the Spanish Aerobiological Network (REA) (Dominguez et al., 1992), where slides were examined along four longitudinal transects that were divided into 2 mm intervals (2 mm = 1-h). In Gdansk, Lodz and Rzeszow a method similar to the one described by Stach (2000) was used. Whereby, pollen grains were counted along twelve latitudinal transects. Each latitudinal transect corresponds to a 2-h interval (Kasprzyk, 2008). The use of two different counting

methods in Poland meant that it was necessary to transform hourly counts into two hourly counts so that a direct comparison could be made between sites. Daily average (00:00–24:00 h) *Ambrosia* pollen counts and diurnal variations (2-h counts) are expressed as grains/m³.

Ambrosia maritima L. is the only native species of *Ambrosia* in Europe (Laaidi and Laaidi, 1999; Laaidi et al., 2003). *A. artemisiifolia* L. (= *Ambrosia elatior* L.), *Ambrosia trifida* L., *Ambrosia tenuifolia* Spreng. and *Ambrosia psilostachya* DC. (= *Ambrosia coronopifolia* Torr. & Gray) are native to North America and have been accidentally introduced, probably with imported cereal grain (Laaidi and Laaidi, 1999; Stepalska et al., 2002; Makra et al., 2004; Tamaracaz et al., 2005). *A. tenuifolia* (silver ragweed) is present only in France and Spain (Tamaracaz et al., 2005) and the distribution of *A. psilostachya* (perennial ragweed) is uncertain due to its confusion with other species (Rich, 1994). *A. trifida* (giant ragweed) can be locally abundant but the most widespread species is *A. artemisiifolia* (common or short ragweed) (Rich, 1994; Dahl et al., 1999; Rybníček et al., 2000; Makra et al., 2004).

2.2. Climate

Poland has a temperate continental climate with both maritime and continental influences. In general, the climate in the North and West of Poland is largely maritime, with cool, wet summers and mild winters, whereas the climate in eastern parts is distinctly continental with more severe winters and hotter, drier summers. Maximum precipitation occurs in summer, when rainfall is often heavy and thundery. The main pressure systems that affect the weather are the Icelandic low (stronger in winter) and the Azores high (mainly in summer), as well as occasional atmospheric fronts from Asia. Poland has a predominantly western circulation and the majority of winds are from the West, particularly from July to September (METO, 2006; Poland.gov, 2006).

2.3. Back-trajectory analysis, elevation and PBL depth

Back-trajectories are an indication of 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 six hourly intervals from 02:00 on the 7th September 2005 to 20:00 on the 10th September 2005. Each back-trajectory was run for 4 days with 6 hourly steps. The study of diurnal variations in *Ambrosia* pollen counts and back-trajectories at

Table 1 – Pollen-monitoring sites used in this study

Site	Latitude	Longitude	Height above sea level (m)	Height of trap above ground level (m)
Gdansk	54°22'N	18°37'E	40	31
Szczecin	53°26'N	14°32'E	52	21
Zagorow	52°10'N	17°53'E	88	15
Lodz	51°46'N	19°28'E	215	15
Lublin	51°14'N	22°34'E	197	18
Sosnowiec	50°17'N	19°08'E	263	20
Krakow	50°04'N	19°58'E	206	20
Rzeszow	50°01'N	22°02'E	202	12

the eight sites identified three *Ambrosia* pollen episodes that were suitable for further analysis. All times are presented as Central European Summer Time (UTC + 2). Elevation of mountain heights are obtained from the satellite derived CGIAR-CSI SRTM 90m Database: <http://srtm.csi.cgiar.org>. PBL depths from Sosnowiec, Krakow and Rzeszow in Poland (the receiving region) and Bratislava in Slovakia and Debrecen in Hungary (potential source regions) (Fig. 1) were calculated by the Eta meteorological model as described in Stach et al. (2007).

3. Results

3.1. *Ambrosia* pollen counts and meteorological conditions during the study period

Ambrosia pollen concentrations were generally low during the first 14 days of September 2005 except for a short period when a number of ragweed pollen counts >20 grains/ m^3 were recorded (7th–10th September). Daily average *Ambrosia* pollen counts from the 1st to 6th September 2005 were generally below 20 grains/ m^3 (Table 2), which coincided with a period when air masses predominantly approached Poland from the East. There was one notable exception to this, *Ambrosia* pollen counts increased in Szczecin to 36 grains/ m^3 on the 4th September. *Ambrosia* pollen counts recorded at Szczecin may have arrived from a local source, such as populations of *A. psilostachya* that were reported by Puc (2004). *Ambrosia* pollen counts >20 grains/ m^3 were recorded at a number of sites in Poland from the 7th to the 10th September. This corresponded with a period when a stable area of high pressure remained situated over Central Europe and a series of low-pressure centres and fronts moved in towards the British Isles and Scandinavia from the Atlantic. This caused air masses to arrive in Poland from the south, which is confirmed by examining back-trajectories from 02:00 on the 7th September. It should be noted, however, that air masses arriving at Szczecin and Gdansk on the 8th and 9th September came from a more westerly direction (Fig. 1), resulting in small numbers of *Ambrosia* pollen grains being recorded at the two sites (Figs. 2 and 3, and Table 2). *Ambrosia* pollen counts again

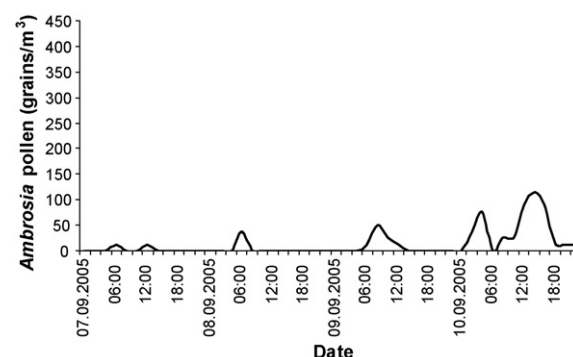


Fig. 2 – Diurnal variation of *Ambrosia* pollen at Szczecin on the 7th, 8th, 9th and 10th September 2005.

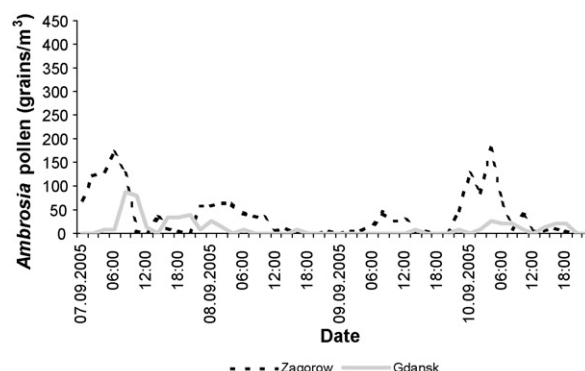


Fig. 3 – Diurnal variation of *Ambrosia* pollen at Zagorow and Gdansk on the 7th, 8th, 9th and 10th September 2005.

dropped below 20 grains/ m^3 on the 11th September. Poland, Slovakia, Czech Republic and Hungary were generally dry during the first 9 days of September, but low pressure brought rain to Hungary on the 10th, which spread to countries in the north on the 11th, 12th and 13th. Winds reverted to a more northerly direction on the 14th. The depth of the PBLs (Table 3) for the selected sites were generally low during the morning in the range 300–400 m, increasing to a maximum of 2000 m and

Table 2 – Daily average *Ambrosia* spp. pollen counts (grains/ m^3) recorded at the 8 sites included in this study from the 1st to the 14th September 2005

Date	Gdansk	Szczecin	Zagorow	Lodz	Lublin	Sosnowiec	Krakow	Rzeszow
01/09/2005	2	1	0	2	2	2	1	1
02/09/2005	1	1	1	2	2	1	0	7
03/09/2005	0	16	0	0	1	0	1	1
04/09/2005	1	36	0	1	1	1	0	1
05/09/2005	0	9	0	0	1	1	0	1
06/09/2005	1	2	4	0	0	19	0	4
07/09/2005	26	2	61	38	17	114	2	29
08/09/2005	4	2	26	68	47	48	1	32
09/09/2005	1	4	15	52	31	40	0	48
10/09/2005	11	21	44	18	88	7	0	58
11/09/2005	1	9	4	6	5	8	0	17
12/09/2005	1	3	3	2	5	4	12	12
13/09/2005	0	1	0	0	2	0	6	1
14/09/2005	0	4	1	0	1	1	4	1

Table 3 – Planetary Boundary Layer (PBL) depths for the receiving region (Sosnowiec, Krakow and Rzeszow) and the potential source region (Bratislava and Debrecen) between 08:00 on the 6th and 18:00 on the 10th September 2005

Time	Date	Sosnowiec PBL height [m]	Krakow PBL height [m]	Rzeszow PBL height [m]	Bratislava PBL height [m]	Debrecen PBL height [m]
08:00	06/09/05	362	381	347	352	312
14:00		2086	1973	1838	1892	1923
20:00		367	387	352	930	316
08:00	07/09/05	639	447	348	379	313
14:00		1941	2002	1846	1902	2229
20:00		1033	1356	453	1414	317
08:00	08/09/05	781	525	348	351	313
14:00		1868	2013	1783	1192	1969
20:00		370	1605	457	1183	319
08:00	09/09/05	573	384	349	768	314
14:00		1960	1997	1599	1879	1977
20:00		1357	1089	726	1693	319
08:00	10/09/05	366	386	349	465	314
14:00		1693	1702	1562	936	1819
20:00		369	390	356	654	320

decreasing again at 20:00. Bratislava had relatively lower daytime PBL depths for part of the period, reaching only 1192 and 936 m for the 8th and 10th of September, respectively.

3.2. *Ambrosia* pollen episode 7th September 2005

Examination of diurnal variations in *Ambrosia* pollen counts on the 7th September 2005 shows that counts at Zagorow peaked between 00:00 and 10:00 (Fig. 3). Back-trajectory analysis for 02:00 (Fig. 4) shows that the air masses that arrived at Zagorow were in Slovakia, Czech Republic and Hungary 12–18 h before. *Ambrosia* pollen grains peaked at

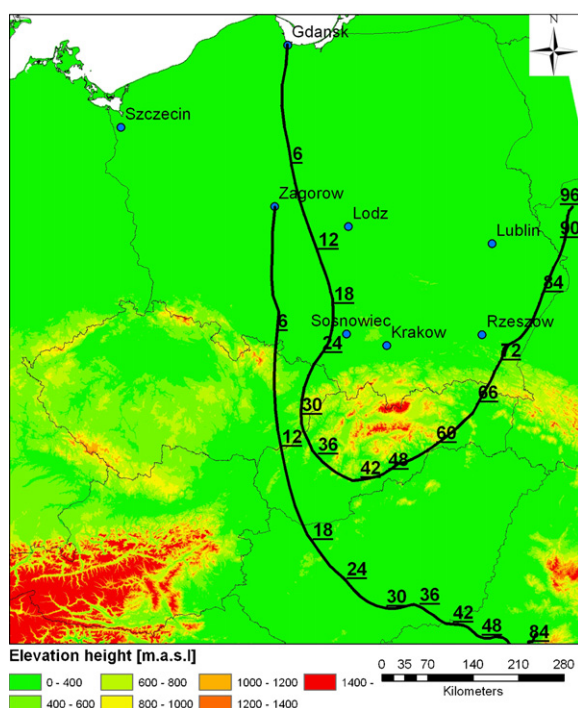


Fig. 4 – Back-trajectory analysis, start of run 02:00 on the 7th September 2005 from Gdansk and Zagorow.

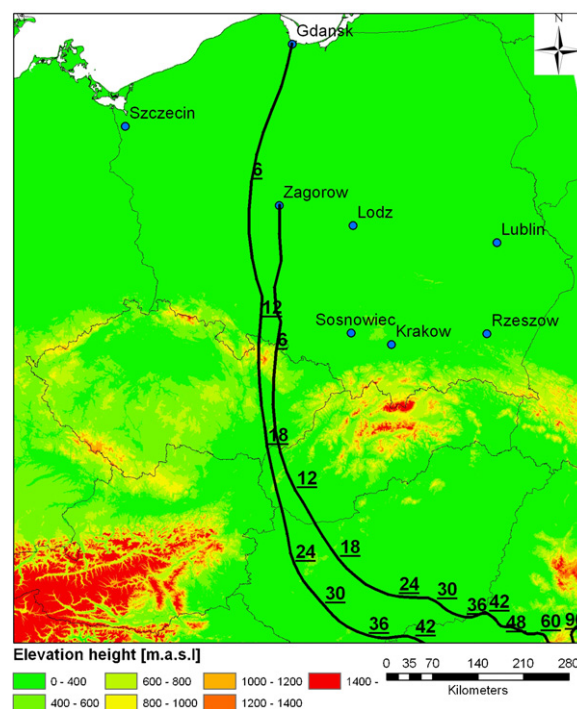


Fig. 5 – Back-trajectory analysis, start of run 08:00 on the 7th September 2005 from Gdansk and Zagorow.

Gdansk between 08:00 and 12:00 (Fig. 3). Back-trajectories calculated at 08:00 (Fig. 5) show that the air mass that arrived in Gdansk passed to the west of Zagorow during the early hours of the morning and was in Hungary 24 h previously. A corresponding peak can also be seen at Sosnowiec during the early hours of the 7th September (Fig. 6).

3.3. *Ambrosia* pollen episode 8th September 2005

Ambrosia pollen counts peaked at Sosnowiec between 22:00 on the 7th and 08:00 on the 8th September 2005 (Fig. 6). Back-

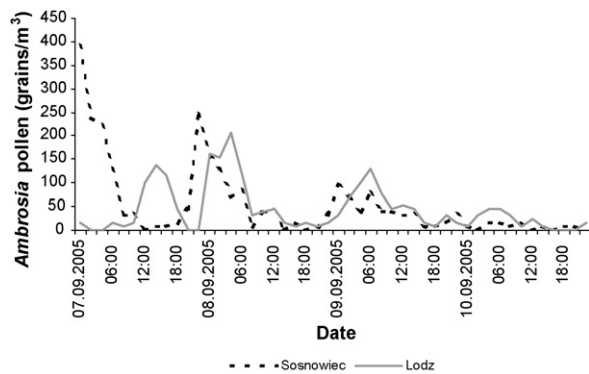


Fig. 6 – Diurnal variation of *Ambrosia* pollen at Sosnowiec and Lodz on the 7th, 8th, 9th and 10th September 2005.

trajectory analysis shows that the air mass that arrived in Sosnowiec at 02:00 was in Hungary 12 h earlier (Fig. 7). *Ambrosia* pollen counts at Lodz (Fig. 6) peaked between 00:00 and 08:00. Back-trajectory calculations for 08:00 show that the air mass arriving at Lodz was to the west of Sosnowiec approximately 4–6 h earlier, and in Hungary 12–18 h before (Fig. 8).

3.4. *Ambrosia* pollen episode 10th September 2005

Ambrosia pollen counts peaked between 22:00 on the 9th September and 02:00 on the 10th September at Rzeszow, and between 02:00 and 08:00 on the 10th September at Lublin (Fig. 9). Back-trajectory analysis carried out at 02:00 on the 10th September (Fig. 10) shows that the air mass that arrived at Rzeszow was in Hungary 12 h before. The back-trajectory for 08:00 (Fig. 11) shows that the air mass that arrived at Lublin

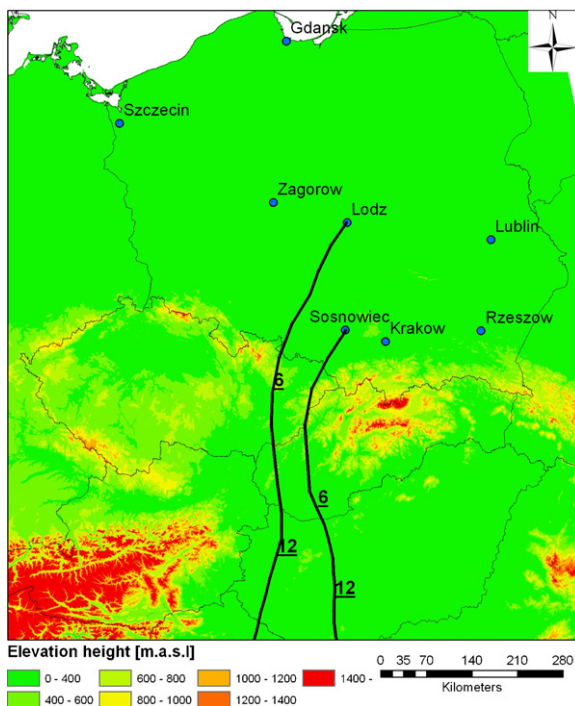


Fig. 7 – Back-trajectory analysis, start of run 02:00 on the 8th September 2005 from Lodz and Sosnowiec.

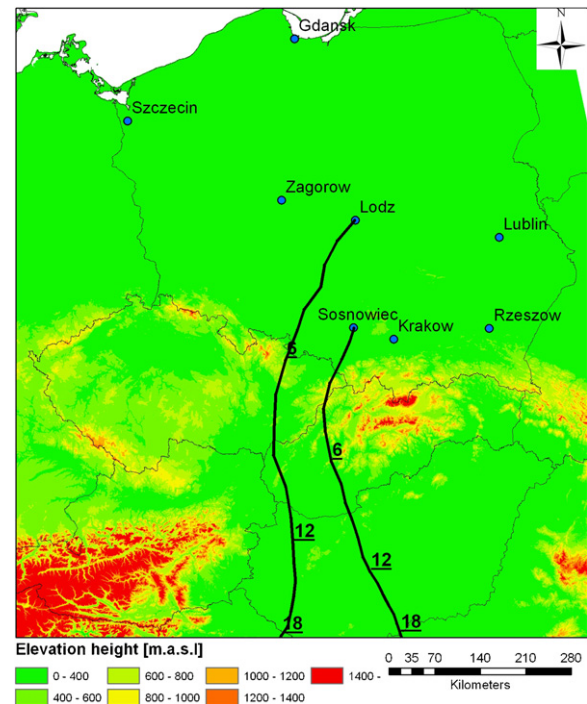


Fig. 8 – Back-trajectory analysis, start of run 08:00 on the 8th September 2005 from Lodz and Sosnowiec.

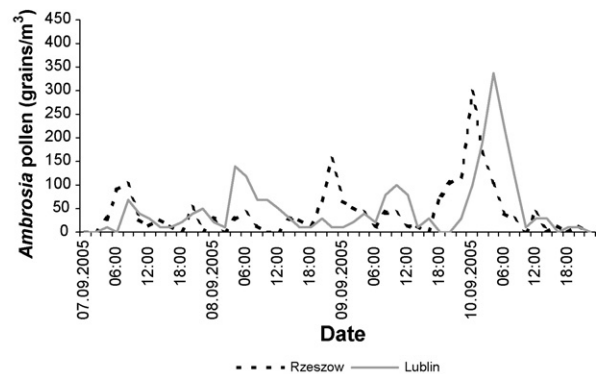


Fig. 9 – Diurnal variation of *Ambrosia* pollen at Rzeszow and Lublin on the 7th, 8th, 9th and 10th September 2005.

passed near to Rzeszow about 6–8 h before and was in Hungary 18 h previously. Peaks in *Ambrosia* pollen concentrations can also be seen during the morning of the 10th September at Zagorow (Fig. 3) and Lodz (Fig. 6). Back-trajectory calculations for 08:00 (Fig. 11) show that the air masses arriving at Zagorow and Lodz also passed over Hungary and the Czech Republic during the preceding 24 h. In addition, a peak in *Ambrosia* pollen was recorded at Szczecin between 12:00 and 18:00 (Fig. 2), but it should be noted that a peak in the afternoon could also indicate a more local source.

3.5. *Ambrosia* pollen counts at Krakow 7th–10th September 2005

The measurements show that *Ambrosia* pollen was present in Krakow in very low quantities from the 7th to the 10th of

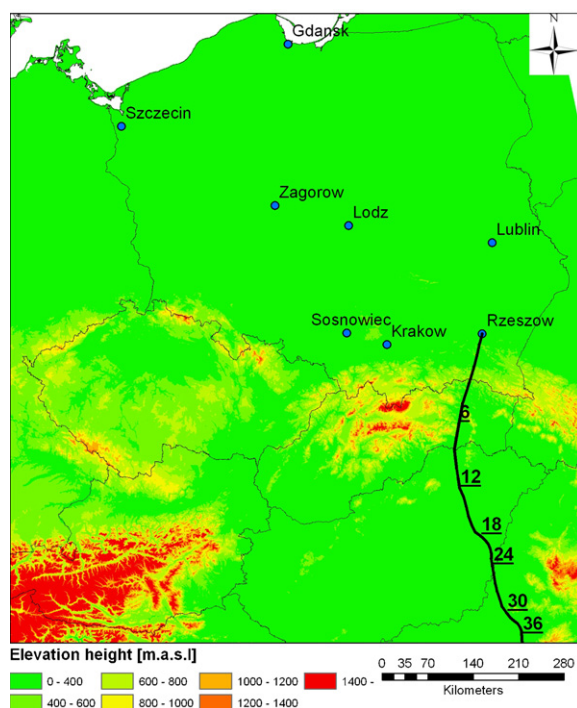


Fig. 10 – Back-trajectory analysis, start of run 02:00 on the 10th September 2005 from Rzeszow.

September (Table 2). A selection of back-trajectories calculated for the study period (Fig. 12) show that the air masses passed the central part of the Carpathian Mountains for much of the time.

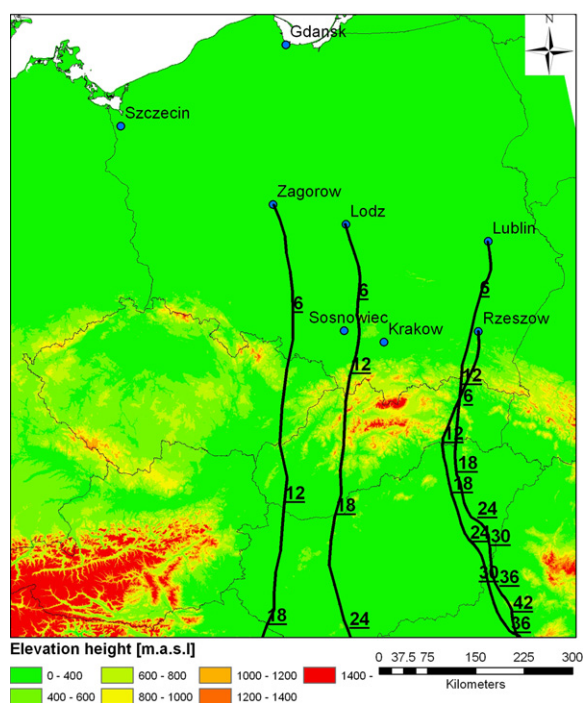


Fig. 11 – Back-trajectory analysis, start of run 08:00 on the 10th September 2005 from Zagorow, Lodz, Lublin and Rzeszow.

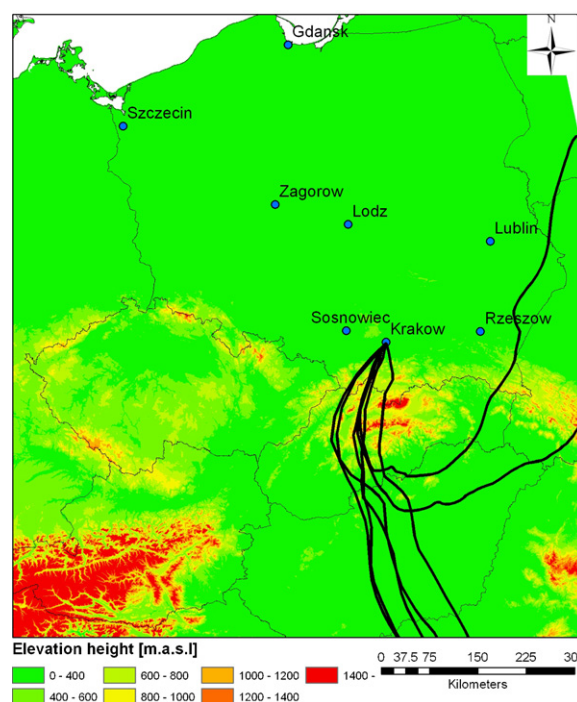


Fig. 12 – Selection of back-trajectories from Krakow, start of trajectory runs: 02:00 and 08:00 on the 7th September 2005; 02:00, 08:00 and 14:00 on the 8th September 2005; 02:00 and 08:00 on 10th September 2005.

4. Discussion

In terms of allergy in Europe, the annual species *A. artemisiifolia* is the most widespread and the most important of the *Ambrosia* genus (Rich, 1994; Dahl et al., 1999; Rybníček et al., 2000; Makra et al., 2004). *A. artemisiifolia* produces entirely by seed (Rich, 1994) and is a prodigious coloniser. Each plant can produce approximately 3000–60,000 seeds, and the seeds can remain dormant for at least 39 years if conditions are unsuitable for germination (Rich, 1994; Comtois, 1998; Dahl et al., 1999; Peternel et al., 2005; Tamaracaz et al., 2005). *A. artemisiifolia* favours a warm continental climate and dry soils (Dahl et al., 1999; Stepalska et al., 2002; Peternel et al., 2005; Tamaracaz et al., 2005). The most ragweed contaminated places in Europe are Hungary, Croatia, and parts of France (the Rhône-Alps region and Burgundy) (Laaïdi et al., 2003). However, ragweed is also spreading in areas such as northern Italy, Switzerland, Austria, the Czech Republic, Slovakia, Bulgaria, Bosnia, Serbia, Romania, Ukraine and European Russia (Makovcová et al., 1998; Dahl et al., 1999; Rybníček et al., 2000; Laaïdi et al., 2003; Makra et al., 2004; Peternel et al., 2005; Tamaracaz et al., 2005). In the areas considered to be centres of ragweed pollen production, such as France and Hungary, ragweed pollen is the commonest cause of allergy symptoms during late summer (Dahl et al., 1999). In Poland, where most of the ragweed pollen is considered to be allochthonous (originating from outside the country), studies showed that 42% of patients who had pollen allergies but did not show symptoms of allergy during the *Ambrosia* pollen season were sensitised to *Ambrosia* allergens (Obtulowicz et al., 1995; Dahl et al., 1999).

Ragweed populations do not tend to thrive under a maritime climate and in northern Europe the growing season is too short for seed maturation (Comtois, 1998; Dahl et al., 1999; Saar et al., 2000). *Ambrosia* has been recorded as far north as Poland, the Baltic States and even Sweden but populations are often ephemeral and scattered and reliant on the regular introduction of seeds from outside sources (Dahl et al., 1999; Saar et al., 2000; Stepalska et al., 2002). For example, *A. artemisiifolia* has been recorded in Poznań in the past (Zukowski, 1960; Jackowiak, 1993) but recent surveys have shown that these areas are no longer populated (Stach, 2006). Ragweed plants are likely to be present in Poland because Stach et al. (2007) showed that *Ambrosia* pollen that arrived in Poznań during the afternoon was brought by air masses that generally remained within the borders of the country for 24 h or longer. Ragweed rarely reaches maturity in northern latitudes and so the occurrence of *Ambrosia* pollen in Poland may be reliant on conditions being appropriate for both germination and pollination or long-range transport (Stach et al., 2007).

This study, which combines measured pollen concentrations and meteorological model calculations, supports the hypothesis that the long-range transport of *Ambrosia* pollen to Poland is intermittent and mainly related to the passage of air masses over and around the Carpathian and Sudetes mountains. Our results show that *Ambrosia* concentrations were generally low during the first 14 days of September 2005 except for a short period when a number of ragweed pollen counts >20 grains/m³ were recorded (7th–10th September). During these episodes, diurnal variations in *Ambrosia* pollen at several monitoring sites show considerable amounts of *Ambrosia* pollen at night or early in the morning. Assuming that pollen release occurs mainly during the day (Bianchi et al., 1959), it is likely that the measured *Ambrosia* pollen recorded in Poland during this study originated from another area. Trajectories for the investigated period show that the air masses predominantly arrived from the Czech Republic, Slovakia and Hungary via the Morawy Gate and Low Beskid passes. PBLs in Slovakia and Hungary (potential source areas) generally had a depth of between 1500–2000 m during day-time. The episodes are therefore associated with hot dry weather, deep PBLs in the source areas and winds from the south.

Furthermore, diurnal variations of *Ambrosia* pollen recorded on the 10th September 2005 at Rzeszow and Lublin (Fig. 9) show peaks of similar size and shape. The peak at Lublin occurred approximately 6 h later than at Rzeszow. The trajectories indicate that the air masses arriving at Lublin passed the Rzeszow area approximately 6–8 h earlier and that the potential *Ambrosia* pollen source area may be Slovakia or Hungary. Similar observations were found for Sosnowiec and Lodz on the 8th and 9th of September (Figs. 7 and 8). The combined results of pollen measurements and trajectories indicate a plume of *Ambrosia* pollen travelling up through Poland during these periods. Conversely, trajectories calculated at Gdansk and Szczecin for 14.00 on the 8th September indicate source regions other than Slovakia and Hungary (Fig. 1). Very little *Ambrosia* pollen was recorded during this time at either Gdansk or Szczecin (Fig. 3), which further supports our hypothesis that the long-range transport of

Ambrosia pollen is mainly related to the passage of air masses from source regions in the south.

The calculated PBLs in the possible source regions (Table 3) had a depth that were similar to the height of the main part of the Carpathian Mountains found to the south of Krakow. Trajectories for the Krakow area indicate passage over these mountains from the source regions, but little *Ambrosia* pollen was measured at Krakow during the study period. This leads to a rejection of the hypothesis that pollen grains are transported over the Carpathians, or at least the central part, despite a PBL with a depth that was similar to or deeper than the height of the mountain range. However, the applied trajectory model may be too simple a tool to estimate air mass transport over the Carpathians. Airflow patterns over mountains are known to be complex and difficult to quantify with atmospheric transport models (Pérez-Landa et al., 2007a,b). If *Ambrosia* pollen grains were transported over the mountains, then local meteorological factors may have made the pollen stay in the air above the Krakow area and transported them further into Poland.

The results of this study indicate that deep PBL levels promote long-range transport. Deep PBLs usually includes large surface heat fluxes and convection enabling distribution of the pollen grains throughout the entire PBL. If pollen grains are elevated to the top of deep PBLs, pure gravitation settling may take several days. Pollen may therefore be carried long distances on the synoptic scale flow. It is very likely that the deep PBLs may be found in other *Ambrosia* rich regions too. Consequently, regions other than Slovakia and Hungary may also act as sources of *Ambrosia* pollen, thereby supporting the work of Saar et al. (2000). Furthermore, our results show that long-range transport from Slovakia and Hungary may reach as far north as Gdansk (Figs. 4 and 5). It is therefore likely that deep PBLs in Slovakia and Hungary could introduce *Ambrosia* pollen via long-range transport to countries neighbouring Poland such as Germany, Denmark, the Baltic countries and possibly Sweden.

Trajectory models should be considered a simple tool for estimating air mass transport, especially in mountain regions. More sophisticated Eulerian models could be applied to study these episodes and to explain what happened in the Krakow area. However, Eulerian models generally require knowledge of sources such as emission inventories. Emission inventories of chemical air pollutants are common and readily available (Olivier et al., 1998; Hertel et al., 2002; Vestreng et al., 2005), but emission inventories for pollen sources are scarce and to our knowledge an emission inventory for *Ambrosia* has not yet been produced. This justifies the use of a trajectory model for the analyses. Furthermore, despite the limitations of trajectory models, trajectories combined with pollen measurements were able to follow the progress of *Ambrosia* pollen plumes through Poland.

5. Conclusion

We have demonstrated how Lagrangian back-trajectory models can be used to investigate possible transport mechanisms of *Ambrosia* pollen from potential source regions. Our studies therefore extends the previous work carried out by

Stach et al. (2007) where the measured atmospheric content of *Ambrosia* pollen was separated into two components: locally emitted and long-range transport. This study also furthers the work of Saar et al. (2000), Belmonte et al. (2000) and Cecchi et al. (2006) by identifying source regions as well as possible transport mechanisms from these source regions.

Acknowledgements

This work was partly funded by the European Union's Sixth Framework Programme through the Marie Curie Actions Transfer of Knowledge Development Scheme. European project MTKD-CT-2004-003170. Polish Ministry of Education and Science grant 128/E-366/6 PR UE/DIE265. This work was also partly funded by the Copenhagen Global Change Initiative (www.cogci.dk). The authors would like to thank the National Centre for Environmental Prediction (NCEP) for providing input data to the Eta model and for providing verifying meteorological observations exchanged under the World Meteorological Organization (WMO) World Weather Watch Programme. The results presented here address two of the main scientific challenges described in COST Action ES0603 (EUPOL) (<http://www.cost.esf.org/index.php?id=1080>), specifically Work Package 1 (pollen production and release) and Work Package 2 (pollen atmospheric distribution and interaction).

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