

Modelling analysis of source regions of long-range transported birch pollen that influences allergenic seasons in Lithuania

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Abstract This study analyses the spatial and temporal distribution of regional and long-range transported birch (*Betula* L.) pollen in Lithuania and the neighbouring countries. The potential long-range transport cases of birch pollen in Lithuania were analysed for the whole period of available observations, 2004–2007. The birch pollen was recorded at three measurement stations in Lithuania by using Hirst-type volumetric spore traps. The phenological observations in Lithuania were also used for the detection of potential long-range transport-induced episodes. Two variants of the regional and continental scale atmospheric dispersion model SILAM

(Lagrangian and Eulerian) in an adjoint mode (used for inverse dispersion modelling and data assimilation), and the trajectory model HYSPLIT were employed to evaluate the source origins of the observed pollen. During four seasons in 2004–2007, we found in total 24 cases, during which remarkable pollen concentrations were recorded before the local flowering season. According to modelling, most of these were originated from the sources outside Lithuania: Latvia, southern Sweden, Denmark, Belarus, Ukraine and Moldova, possibly, also coastal regions of Germany and Poland. Two episodes were attributed to local early-flowering birch trees. The spatial and temporal patterns of the long-range transport of early pollen to Lithuania were found out to be highly variable; the predicted source regions for the cases considered were similar only for some dates in 2004 and 2006. During the analysed period, we found both cases, in which the predictions of the SILAM model variants and those of the HYSPLIT model were similar, and cases, in which there were substantial differences. In general, for complicated atmospheric circulation patterns the model predictions can be drastically different, with a tendency of trajectory model to fail reproducing the key episode features.

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1 Introduction

Pollen concentrations in the atmosphere depend both on pollination of local flora and on the atmospheric transport from adjacent and distant regions. In analysing the temporal and spatial variations of pollen concentrations, it is therefore necessary to address also meteorological and environmental factors, such as temperature, precipitation, relative humidity, sunshine durations and wind speed and direction (Clot 2001; Laaidi 2001; Latałowa et al. 2002; Porsbjerg et al. 2003). These factors are crucial both for the release of the pollen grains and for their atmospheric transport (Sofiev et al. 2006a; Vogel et al. 2008).

Airborne pollen forecasting based on local observations is a beneficial tool in health care (Hidalgo et al. 2002; Smith and Emberlin 2006; WHO 2003). However, in many cases, it is necessary to also take into account the long-range transport, which can be evaluated only by using atmospheric dispersion models. Several scientific groups currently address the modelling of *Betula* L. pollen, which is one of the most significant sources of airborne allergy in northern, central and eastern Europe (D'Amato et al. 2007). It has been shown that long-range transport can have a substantial influence on the birch pollen season being particularly important before the start or after the end of the local flowering (Ranta et al. 2006; Sofiev et al. 2006a, 2008b; Siljamo et al. 2007, 2008b; Karppinen et al. 2007; Skjøth et al. 2007; Mahura et al. 2007).

The most common method for tracing the transport of airborne pollen is forward or backward trajectory modelling using various Lagrangian trajectory models, such as the HYSPLIT model, which has been developed by the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (Van de Water and Levetin 2001; Gassmann and Pérez 2006; Šaulienė and Veriankaitė 2006; Cecchi et al. 2007; Mahura et al. 2007). A more sophisticated methodology for a quantitative analysis of the observational footprints is adjoint dispersion modelling, which is based on numerical solution of the adjoint (inverse) dispersion equation (Marchuk 1982). The idea of the method is to explicitly compute the sensitivity of the observed values to emission fluxes, chemical transformations and meteorological processes that can affect the particular observation.

Adjoint methods have previously been used in observational analysis on a local scale (Kuparinen 2006; Kuparinen et al. 2007a, b; Rannik et al. 2003) and in the source apportionment of greenhouse gas emissions (Bergamaschi et al. 2005). The methodology has also recently been used in the analysis of regional air quality (e.g. Saarikoski et al. 2007; Prank et al. 2008) and the dispersion of pollen (Sofiev et al. 2006a, b; Siljamo et al. 2008b).

In general, the adjoint modelling is a more versatile and reliable method for evaluating the sources of pollutants, compared with the more commonly used trajectory analyses. First, the atmospheric dispersion and removal processes can be properly taken into account. Secondly, the solution of the adjoint dispersion equation provides a quantitative prediction of the geographic areas, where the sources responsible for the observed concentrations are located, and estimates their contributions to the measured concentrations. Thirdly, adjoint modelling can also allow for the linear (or linearised) chemical and physical transformation processes. In case of trajectory analyses, merely the transport paths of air parcels can be modelled following the mean air flows. It does neither take into account the physical and chemical properties of the pollutants nor the turbulent mixing.

The adjoint modelling is a standard technique to evaluate the footprint of the observations. A (ground) surface footprint of a single observation is by definition a surface area, which delineates the sources that are responsible for the observed atmospheric concentrations. As a simplification, all sources located within the footprint area would influence this observation, and no sources located outside the footprint area would affect it. However, the detailed contributions of these sources can be probabilistically evaluated, i.e. the model can be used to evaluate the probability of a specific air parcel to reach the observational site. By integration over all the sources and transport pathways, one can evaluate the spatial and temporal distribution of the probability for the sources to impact a specific measurement. The source areas, for which this probability does not vanish, comprise the footprint that corresponds to this particular observation. Computations of the footprint with standard dispersion models are prohibitively resource-consuming, while the adjoint modelling generates the solution with reasonable efforts (Marchuk 1982; Sofiev et al. 2006b).

The aims of this study were (1) to analyse the beginning of the pollination seasons in Lithuania during 4 years, (2) to study the prominent cases of potential long-range transport that could have substantially influenced the concentrations, (3) to intercompare the predictions obtained using various models and analyse the differences and (4) to characterise the main source areas of birch pollen observed in Lithuania.

2 Materials and methods

2.1 Observations of pollen and phenological data in Lithuania

Aerobiological observations in Lithuania were started at Šiauliai University in 2003. The second station was set-up in Klaipėda in 2004, and the third one in Vilnius, the capital of Lithuania, in 2005. All these stations are currently in operation and provide the information to the European Aeroallergen Network, EAN (<http://www.polleninfo.org>). The coordinates of the easternmost station in Vilnius are 25°16'05E, 54°40'40N, and the measurement height is 18 m above the ground level. The aerobiological station in Klaipėda (21°07'32E and 55°45'20N) is situated at the coast of Baltic Sea, and its measurement height is approximately 20 m above the ground level. The measurement height of the northernmost station in Šiauliai (23°18'32E, 55°55'36N) is 18 m above the ground level.

The distances between the stations of Vilnius and Šiauliai, Vilnius and Klaipėda and Klaipėda and Šiauliai are 214, 311 and 160 km, respectively. These monitoring stations are sufficiently closely located to allow for an analysis of the regional characteristics of the pollen seasons. The stations are able to reproduce the spatial distributions patterns of pollen over most of Lithuania. On the other hand, long-range transport episodes commonly affect more than one of these sites.

The observations can identify pollens of 37 different pollen types of anemophilous plants. Pollen is recorded using the Hirst-type seven-day recording volumetric traps (Hirst 1952). Observations are commonly daily average values; however, for the present study several episodes were reanalysed, using measured data with a temporal resolution of 2 h.

Sampling surfaces, preparations of the slides, pollen counting and concentration calculations followed the standard methodology of Mandrioli et al. (1998); the countings followed the 12 vertical sweeps of the slides.

Betula L. genus pollen was selected as the example of this study, as it is one of the most common trees in Lithuania (Saulienė and Motiekaityte 2005; Šaulienė et al. 2007), and its pollen is frequently observed also before the start of local birch flowering. *Betula pendula* Roth accounts for about 19.9% of the total area of forests in Lithuania (Navasaitis et al. 2003). For the analysis of possible pollen episodes created by the long-range transport (LRT), we also used the data of the aerobiological networks of Finland, Denmark, Sweden and Latvia.

The phenological data were provided by the Lithuanian Hydrometeorological Service and the Šiauliai University. The data set included information from 11 phenological stations in 2004 and 2005 and from 12 stations in 2006 and 2007, which together represent most of the Lithuanian area. The observations of the start of flowering (the parameter used in the current study) were carried out daily from the beginning of March to the end of May. As described by Estrella et al. (2006), the beginning of flowering was defined as the day, on which the first blossoms are fully open on at least three spots on a plant. More details and comparison with the phenological observations in other countries can be found in Siljamo et al. (2008a).

2.2 Modelling tools

The models used in this study included: (1) the trajectory model HYSPLIT for computing the individual backward trajectories, (2) the Lagrangian random-walk particle version of the SILAM model, which has been used to compute ten thousands of random-walk particle trajectories for each of the considered cases; this model also explicitly included removal processes and (3) the Eulerian version of the SILAM model, which was used to evaluate a complete adjoint dispersion equation. These modelling systems were driven using meteorological inputs by several numerical weather prediction models. The variability of the predictions of such a collection of models results also to some insight regarding the uncertainty of the model predictions and complexity and predictability of the cases.

2.2.1 The backward trajectory calculations with the HYSPLIT model

We used the backward trajectory calculations with the isobaric HYSPLIT 4 model (Hybrid Single-Particle Lagrangian Integrated Trajectory), which is provided by the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (Draxler and Rolph 2003). The simulations were based on the meteorological NCEP/NCAR reanalysis data (global coverage from 1948 to present) for 2004–2007. The spatial resolution of this input data set is approximately 250 km.

A set of backward trajectories were generated, for each of the available two (2004) or three (since 2005) aerobiological stations of Lithuania, for each of the considered arrival times. The air parcel motions were computed on the isobaric surfaces with the starting heights at 500, 1,000 and 1,500 m above the ground level in the model. In some specific cases, we used an additional low-level trajectory, which was started at a height of 50 m above the ground, to highlight the near-surface transport direction. Each 24-h period was represented by 12 arrival times at every 2 h starting from midnight. The duration of the trajectories varied from 48 to 72 h from case to case. In total, a few thousands of backward trajectories were computed and associated with the corresponding daily pollen observations at the aerobiological stations. Clearly, in this article, it is possible to present in graphical form only a very small fraction of these trajectories, i.e. those, which are best representative for the episodes considered.

2.2.2 The observational footprint computations using the SILAM dispersion modelling system

The air quality and emergency dispersion modelling system SILAM can be used for both forward and adjoint simulations, for which two cores are available, Lagrangian particle and Eulerian (<http://silam.fmi.fi>). The Lagrangian SILAM core is based on a random-walk particle model (Sofiev et al. 2006b). The Eulerian core of SILAM has been constructed on the basis of the advection routine of Galperin (1999, 2000) and the extended resistance analogy of Sofiev (2002). Dry and wet deposition treatments and overall architecture are based on the DMAT modelling system (Galperin et al. 1996; Galperin and Sofiev 1998; Sofiev 2000).

For an outline of the Eulerian version of SILAM, the reader is also referred to Sofiev et al. (2008a). For pollen applications, the model has been used for both source apportionment and forward dispersion simulations (Sofiev et al. 2006a, 2008b; Siljamo et al. 2007, 2008b).

In this study, we have used both the Lagrangian and Eulerian versions of the SILAM model, which have been used in the adjoint mode. Both versions were executed with a time step of 15 min and evaluated the transport during 72 h backward in time, for each case of suspected long-range transported pollen recorded at each of the stations. For the Lagrangian particle simulations, we assumed a well-mixed atmospheric boundary layer and fixed diffusion intensity in free troposphere. Following the standard procedure of Monte-Carlo Lagrangian particle models, turbulent mixing was represented via random relocation of a large number of particles (10,000 in the current study) released for each case. The Eulerian system was configured to include 10 vertical grid layers up to a height of 4 km above the ground. The horizontal grid cell size was 30 km, and the domain of simulations covered almost the whole of Europe.

The so-called source term of the adjoint simulations consisted of the actual observed pollen concentrations at the aerobiological stations in Lithuania. Since the pollen grains resemble inert aerosols (Sofiev et al. 2006a), we utilised the aerosol physico-chemical module, with the properties of particulate matter equal to those of birch pollen. Vertical profile of the source term was set to be a uniform concentration at the altitude interval from 18 to 100 m, while the analysis of the footprint was focused on the lowest model layer (0–20 m), where the birches are located. The output variables included concentration, wet deposition, dry deposition and probabilistic terms, such as a 2D surface footprint and its 3D extension, which also includes the vertical distribution of the probability density.

Two sources of meteorological information were used for the forecasts. First, we used the RCR-HIRLAM predictions (Regular Cycle Reference-High Resolution Limited Area Model, Undén et al. 2002), variants HIRLAM v.6.2.1 for the analysis of cases in 2004 and 2005, and HIRLAM v.6.3.7 in 2006 for the cases in 2004–2006. The horizontal resolution is 0.2°, i.e. about 20 km, and there were 40

vertical hybrid levels in all cases. Second, we used the ECMWF predictions (European Centre of Medium Range Weather Forecast, <http://www.ecmwf.int>) for the cases in 2007. The horizontal resolution is 0.25°, i.e. about 25 km, and there were 74 vertical hybrid levels. We used short-term model forecasts (from +3 and +6 h, and from +3 to +12 h for the HIRLAM and ECMWF-based simulations, respectively), which provided the meteorological fields to the dispersion model with 3-h intervals.

2.3 Selection of LRT-induced episodes in 2004–2007

In this study, we refer to pollen originated from outside the national (Lithuanian) borders as the long-range transported. Strictly speaking, in some cases this could refer also distances on a regional scale (a few hundreds of km), which is most commonly not considered to be long-range transport in atmospheric science. The Lithuanian aerobiological stations cannot be representative on such scales, and dispersion modelling is needed for the interpretation of the observations.

We have compared the start of the pollen seasons using the various criteria, which were defined previously. To select the episodes for the analysis, we compared four types of dates.

First, using the aerobiological observations, one can select the date of the first non-zero pollen count as the start of the season (hereinafter referred to as “the date of the first non-zero count”). Secondly, following Goldberg et al. (1988), we defined the 2.5% the start of the pollen season recorded by the aerobiological stations as the date when the cumulative pollen count reached 2.5% of the annual total (hereinafter referred to as “the 2.5% season start”). Thirdly, from phenological observations, we selected the earliest date when at least one station reported the start of flowering (the “earliest flowering date”). Finally, the date of phenological massive pollination date when most of trees were flowering was called as the “median date” of the season.

Siljamo et al. (2008a) showed that the irreducible variability of the phenological start of birch flowering in Lithuania is at least 3–4 days on all spatial scales down to 1 km. This corresponds to the time difference between the first-reported phenological flowering date and the median flowering date. For the

aerobiological observations, this time lag approximately corresponds to the difference between the first-observed non-zero daily pollen count and the start of the season defined by the 2.5% criterion. It is therefore reasonable to compare the dates of the earliest phenological data with those of the first non-zero pollen counts and the dates of the median phenological date with those of the 2.5% season start.

With the earlier mentioned definitions, the case was considered as possibly LRT-influenced if either of the aerobiological dates was before the corresponding phenological date. All episodes of substantial pollen counts during such periods were included into the analysis.

3 Results

As seen from the data presented in Fig. 1, the first non-zero pollen concentrations are always observed before the earliest phenological flowering date; however, the temporal difference was large only in 2004. The selection procedure of the LRT episodes has highlighted 24 cases, which presumably originate from LRT as presented in Fig. 2. All cases were analysed day-by-day using the three models. In the following, we have selected a few of the most illustrative episodes for each year.

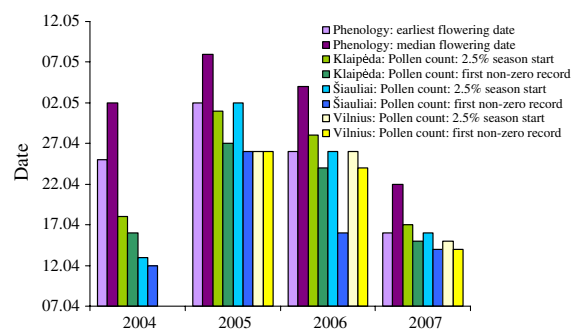
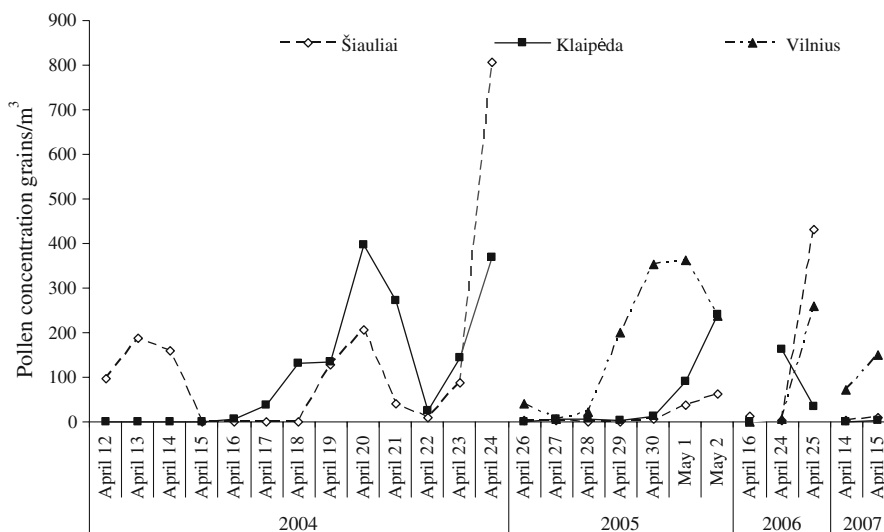


Fig. 1 The start dates of the birch seasons in Lithuania according to different criteria: the earliest reported phenological flowering start in Lithuania (“the earliest flowering date”), the massive pollinating of most of trees in Lithuania (“the median flowering date”), the first non-zero daily pollen count for each station (“the first non-zero record”) and the start of aerobiological season according to the 2.5% criterion for each station (“the 2.5% season start”)

Fig. 2 Pollen concentrations recorded between the date of the first remarkable pollen count, until the earliest flowering date reported by phenological stations, in Lithuania from 2004 to 2007. Note overlapping-count curves reported by both Šiauliai and Klaipėda in 2007



3.1 Possible LRT episodes in 2004

In 2004, there were substantial pollen counts before the start of birch season at both aerobiological stations that were in operation in Lithuania. The sum of pollen concentrations until the earliest phenological flowering date was 1,723 grains m^{-3} at Šiauliai and 1,513 grains m^{-3} at Klaipėda. In comparison with other years, the year 2004 was characterised by the longest period of LRT-influenced concentrations, which lasted for almost 2 weeks (cf. Figs. 1, 2). We present in the following, the analysis for the 13, 20 and 24th of April for the aerobiological station at Šiauliai and for the 20th and 21st of April for the station at Klaipėda.

The predictions of the three models, Eulerian and Lagrangian variants of SILAM and HYSPLIT have been presented in Fig. 3a–c. Both SILAM simulations showed the north-western direction towards central Sweden and Norway as a part of footprint on both 12 and 13th of April, but also indicated another, less pronounced branch of the footprint from southern Sweden and Denmark. The latter part of the footprint contributed more than 40% to the pollen concentrations recorded in Šiauliai on 12th of April (Fig. 3a1, b1). During the next day (Fig. 3a2, b2), the footprint was shortened and shifted northwards, which excluded Denmark from the potential list of sources leaving only southern and central Sweden, central Norway and western Latvia. In Fig. 3, coastal regions of Germany and Poland are just outside the footprint.

However, position of its borders has limited accuracy determined by the wind direction representation, which leaves certain probability (quite small, though) of these sources to contribute to the episode.

According to HYSPLIT predictions shown in Fig. 3, birch pollen concentrations observed at Šiauliai aerobiological station during both 12 and 13th April 2004 could originate from the western part of Latvia, central Sweden and Norway (Fig. 3, panels 1c and 2c, respectively). During 12th of April, the sources could also be located in southern Sweden, but not during the next day. However, beginning of April is far too early for any flowering in any of these regions, except for, possibly, southern Sweden or Denmark. Therefore, the HYSPLIT trajectories do not provide adequate information for this episode.

This episode was complicated also from the point of view of the source apportionment. All possibilities of the source locations highlighted by the SILAM footprint have their own complications. In particular, pollen counts in Sweden, south of Stockholm (about 16E, 57N), were zero during the entire episode and several days after it. The footprint suggested even more southwards regions but no pollen counts are available from there. Also, very small or zero counts were reported at Klaipėda and in Denmark (both, however, strongly affected by the cooling effect of the Baltic Sea in spring). The only comparable concentrations were registered near Berlin but this area is far outside the footprint. A possibility of early local flowering also does not look probable because

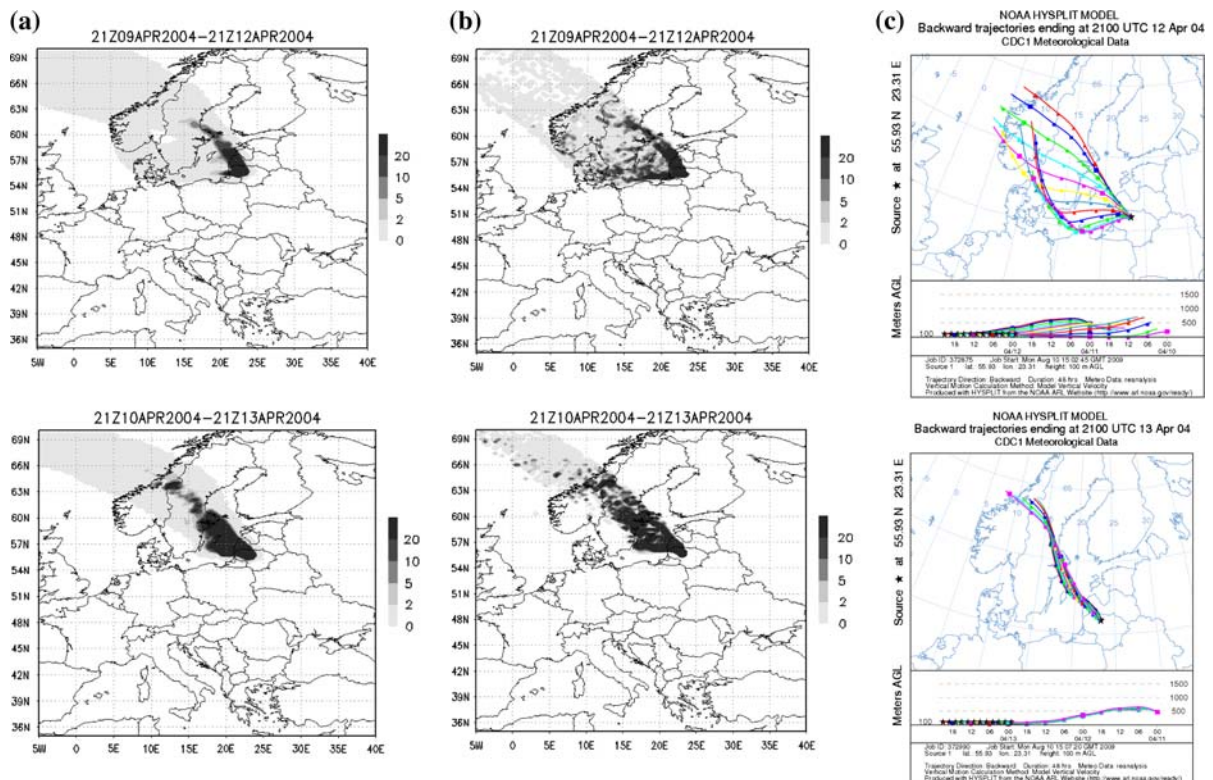


Fig. 3 The predicted footprint for Šiauliai. The *upper row* 1: 12 April 2004, *lower row* 2: 13 April, 2004. *Panels a* (left-hand side figures) Eulerian SILAM, *b* (middle figures) Lagrangian

SILAM, *c* (right-hand side figures) HYSPLIT backward trajectories (example of 100 m starting elevation is shown)

after the peak at Šiauliai concentrations were low at all stations over the region for several days. Such behaviour of the counts is rather common for an LRT episode.

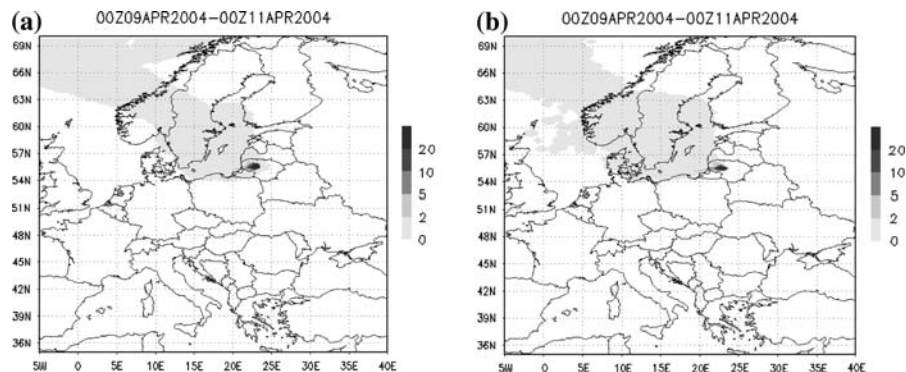
In order to refine the predictions of the potential source areas, we computed also the footprint for the observations on 11th April 2004, when no pollen was measured at any of the Lithuanian stations. As seen from Fig. 4, the possible source area was extensive, but the direction was the same as that of observations on 12th April 2004. Therefore, if the source was located in Sweden, the first flowering day must have been on 10th of April. This pollen would reach Šiauliai by 12 April, and result in the above two-day episode.

An analysis of the meteorological patterns partly clarified the characteristics of the episode and shed some light on the disagreement between the SILAM and HYSPLIT simulations. There was a frontal system that was transported from Sweden to Russia

during the 10th and 11th of April, i.e. just before the non-zero pollen concentrations were recorded at Šiauliai. After that date, a high-pressure area developed over southern Finland (on the 12th of April) was transported towards the Baltic Sea (on the 13th of April) and prevailed over the Kaliningrad region by the 14th of April. Under its influence, the daytime temperatures increased and promoted the start of flowering, which was inhibited during the preceding cold weather and the passage of the front that was accompanied with rain. Therefore, the hypothesis of the flowering in the southern Sweden starting shortly after the front passage seems to be supported by this development.

Potential start of flowering also in western Latvia could also contribute to the episode. However, it is less probable due to generally colder winter and early-spring temperature there. Also, according to the Latvian aerobiological records, birch pollen was not observed there until the 18th of April. Since that date,

Fig. 4 Footprint areas for the zero-count observations for the station of Šiauliai on 11th of April, 2004: Footprints predicted by the SILAM model using **a** Eulerian **b** Lagrangian model variant



substantial amounts of pollen were present until the end of April, which suggests that the flowering started there at least a week after the considered episode. This leaves the southern Sweden as the only possible source of the episode during 10–12th of April in Lithuania.

Finally, an indication on the pollen origin can be derived from the bi-hourly pollen counts for Klaipėda and Šiauliai. They show that in Klaipėda, the concentrations were very small all over the day (a few grains per m^3), but the first grains were recorded already between 4 and 6 a.m. local time, which is too early for local trees to pollinate. Therefore, these pollen counts have to be originated from a release on the previous day somewhere upwind, which is an indication of the pollen originated from distant sources. This analysis, however, is uncertain due to very low pollen concentrations. In Šiauliai, the pattern is totally different: bi-hourly concentrations reach $150 \text{ grains m}^{-3}$ with the first substantial number recorded only in 10 a.m. This timing suggests the presence of the local source that started pollination on this very day, or a powerful distant source with a travel time of $\sim 18 \text{ h}$, which was flowering during the previous day.

Therefore, with the data available, it is hardly possible to arrive at a firm conclusion on the sources of the elevated counts at Šiauliai. More detailed and high-resolution simulations using both adjoint and forward modelling techniques with detailed flowering model validated for the region would be needed for more firm conclusions.

The next case took place a few days later, on 18–21 April 2004, when the count of pollen exceeded $200 \text{ grains m}^{-3}$ at two sites almost synchronously

(Fig. 2). Simulations for the 20th of April (Fig. 5) showed that air masses reached the Šiauliai station from the south-easterly direction. The predicted source regions are then located in the western Belarus, western and southern parts of Ukraine and Moldova.

The pollen counts at Klaipėda increased already on 18th April 2004, when high pollen concentrations were probably originated from central and eastern Europe. The next rise was on 21st of April 2004 when pollen could come from Denmark, Germany, Poland, Belarus, Ukraine and Moldova (Fig. 6).

The weather situation was less complicated during this period: a high-pressure area was located over Russia, and a deep low-pressure system was situated between Iceland and Scotland. This resulted in relatively strong and stable southward winds in Lithuania. For this case, the HYSPLIT model predicted practically the same source areas as both of the SILAM adjoint simulations (Figs. 5, 6). Interestingly, this episode coincides with the first increase of pollen concentrations in Latvia in 2004. Similar levels and synchronous dates suggest that the same distant sources might be responsible for the elevated concentration in both Latvia and Lithuania. However, detailed analysis of this similarity is outside the scope of the study.

The next increase of pollen concentrations took place on the 24th of April. Notwithstanding the phenological observation had not yet shown the start of *Betula* flowering in Lithuania, it is difficult to ascribe so high concentrations (over $800 \text{ grains m}^{-3}$) to long-range transport. Modelling results demonstrated that the remote source areas affecting Klaipėda were the Baltic Sea and west parts of

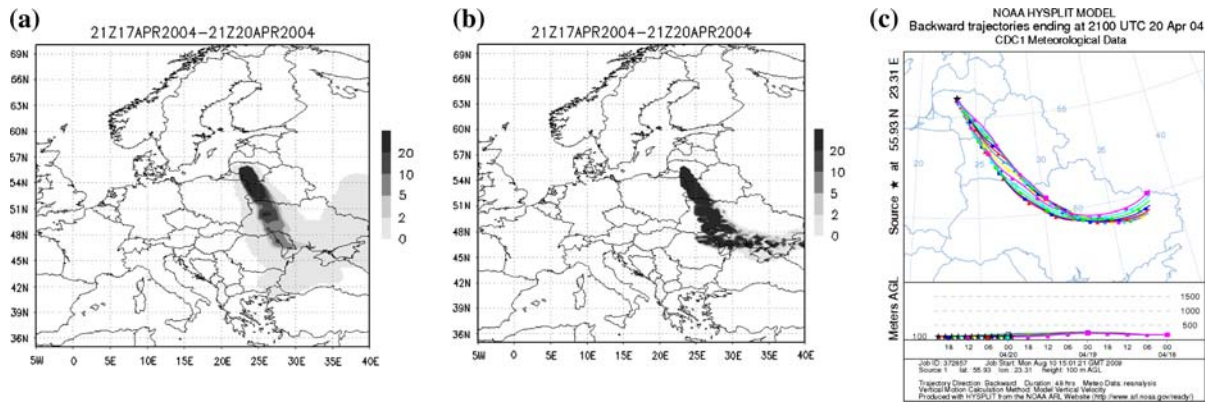


Fig. 5 The predicted footprint for 20 April 2004 for Šiauliai (for all models). *Panel a* Eulerian SILAM, *b* Lagrangian SILAM, *c* HYSPLIT backward trajectories

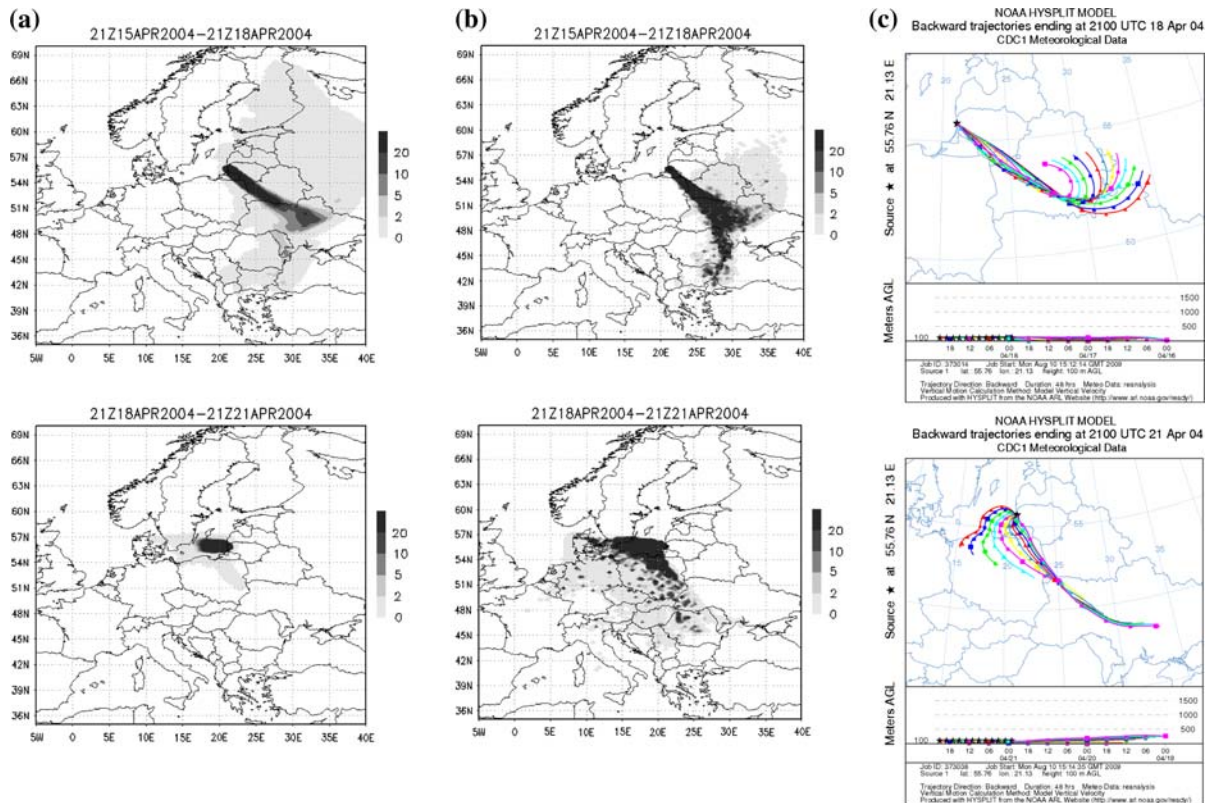


Fig. 6 Predicted footprint for 18 and 21 April 2004 for Klaipėda (for all models). *Upper row 1:* 18th of April, *lower row 2:* 21st of April. *Panel a* Eulerian SILAM, *b* Lagrangian SILAM, *c* the HYSPLIT backward trajectories

Latvia territory, while Šiauliai was under influence of south-east parts of Latvia, north parts of Belarus and some areas of Russia. However, most likely the observed pollen grains were from regional birch forests or immediate surroundings of the stations.

3.2 Possible LRT episode in 2005

In 2005, only one episode was worth consideration: a large amount of birch pollen was observed at the aerobiological station of Vilnius on the 26th and on

the 28–30th of April. The highest daily pollen counts were 616 grains m^{-3} . During this period, only minor amounts of pollen were observed at the stations of Šiauliai (13 grains m^{-3}) and Klaipėda (23 grains m^{-3}).

On the 27–30th of April, a low-pressure system was located to the north of Scotland, but otherwise a high-pressure area dominated over Europe. The winds were therefore light, and the predicted flow field was uncertain. On the 1st of May, a saddle pressure surface over the Baltic countries made the situations even more difficult to predict. After that day, a high-pressure system developed over the Balkan Peninsula and a low-pressure system formed over north-western Russia. This weather pattern induced light north-westerly winds in Lithuania.

According to all model predictions, the highest probability to receive the LRT'ed pollen to Vilnius (Fig. 7) was from southern part of Finland and western part of Latvia, while the footprints of Šiauliai and Klaipėda (not shown) mainly covered the western part of Latvia. Since the time for the birch flowering in Finland was still too early and the observed concentrations in Latvia were very low until 1st of May, the only possible sources of remarkable concentrations in south-east of Lithuania could be in the nearest vicinity of the sites. This possibility is also supported by the fact that counts in Vilnius increased 2 days earlier than in Šiauliai and Klaipėda, despite both of these sites are inside the Vilnius footprint. Therefore, it is plausible that the air masses that were transported from the north (and therefore contained only minor quantities of birch pollen)

received most of the pollen, while these were transported over warm habitats in Lithuanian mainland. The main flowering there started on 2nd of May: concentrations raised on that date at all sites, their footprint (not shown) was mainly confined within the country borders and the phenological records also reported the flowering start. The early trees can start pollinating 1–2 days earlier compared with the main tree population.

3.3 Possible LRT episodes in 2006

In 2006, the peak of concentrations (723 grains/ m^3) was recorded on 25th of April, for which the modelling results show that probable source areas of *Betula* pollen are in northern Europe. During that period, the centre of a high-pressure system over Norway and Sweden was transported to the Gulf of Riga, and further to the St. Petersburg area. The winds within the region were therefore light and the wind directions were variable, finally turning to southerly and south-easterly on 25th April 2006.

According to the predictions of the SILAM model (Fig. 8), the most likely source regions for pollen observed at Šiauliai are to the south and south-east of the site, in Poland, Belarus and the northern parts of Ukraine. The predictions of the SILAM model included substantial temporal variations of wind direction, including a turn of winds by almost 180° during the episode. As a result, the footprint is fairly narrow near the observational site, but is drastically diluted approximately 500 km southwards. In the Eulerian SILAM predictions, the smaller probability

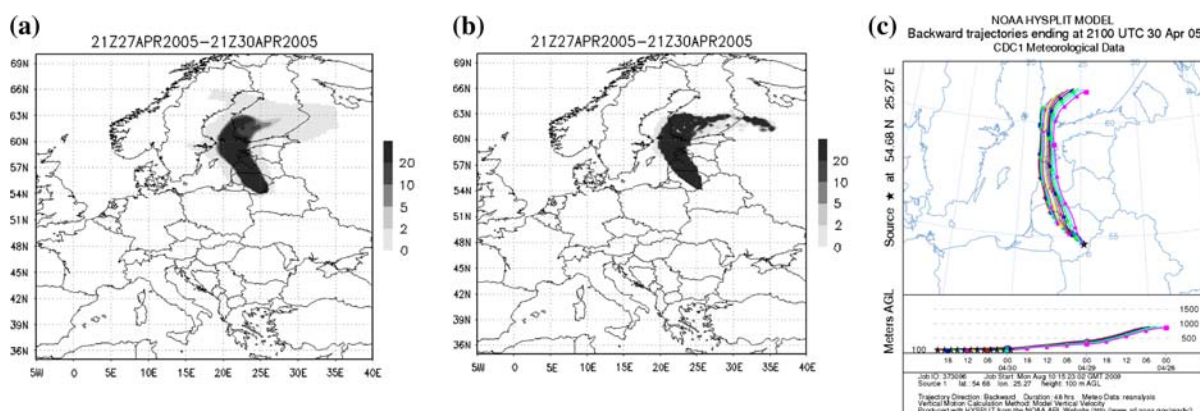


Fig. 7 Predicted footprints for 30 April 2005 for Vilnius (for all models). *Panel a* Eulerian SILAM, *b* Lagrangian SILAM and *c* HYSPLIT backward trajectories

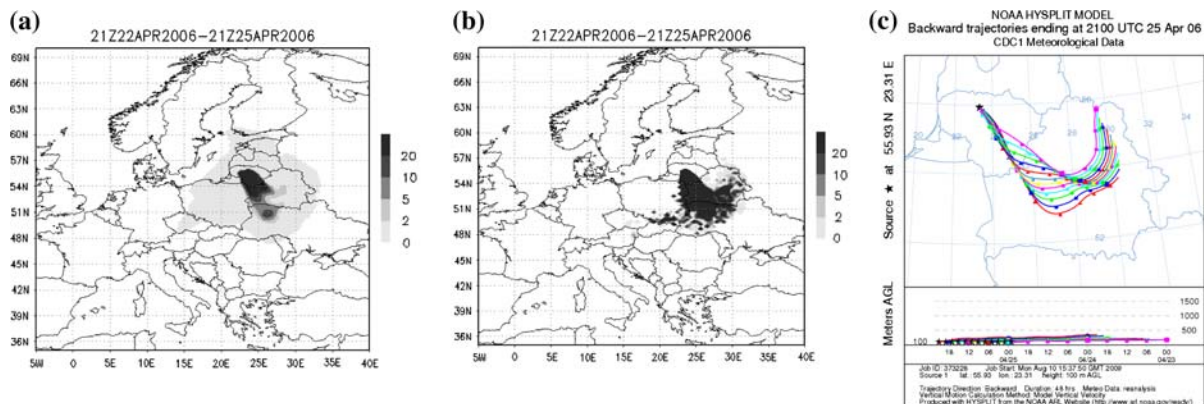


Fig. 8 Predicted footprint for 25 April 2006 for Šiauliai (for all models). *Panel a* Eulerian SILAM, *b* Lagrangian SILAM, *c* HYSPLIT backward trajectories

footprint region extends almost in all directions, even to the north of the site.

3.4 Possible LRT episodes in 2007

In 2007, the elevated concentrations in the middle of April were clearly too early to be originated from the local sources. All aerobiological stations in Lithuania were affected, but the highest concentrations were measured at Vilnius (over 200 grains/m³).

Similarly to the cases considered earlier for 2004–2006, a high-pressure area dominated the synoptic-scale meteorological situation in the region. It was formed to the south-west of Lithuania on the 12th of April, and caused moderate, mainly north-westerly winds. During the next few days, the high-pressure system was stationary, and the wind speeds decreased.

With such a pattern, it is difficult to make firm conclusions regarding the origin of the observed pollen. Moderate concentrations were observed at all Lithuanian sites, substantially before the start of the local flowering. Such conditions commonly can be interpreted to indicate an LRT origin. All predictions of SILAM and HYSPLIT suggested that the source areas would be in northern Europe (predictions not shown here), which looks somewhat surprising, as usually flowering in these areas starts later than in Lithuania. Observations in Latvia showed very low but non-zero concentrations as early as 10–12th of April, with significant counts (~ 50 grains m⁻³) registered since 14th of April. We therefore conclude that unusually early

flowering took place in 2007 in Latvia and, most probably, in Lithuania where the concentrations were higher. A couple of days of difference from phenological observations (the first flowering recorded 16.4) are well inside the uncertainties of such measurements.

4 Discussion

Birch pollen is the most common and the most extensively studied pollinating species in northern, central and eastern Europe. However, substantial problems still exist in forecasting and analysing the temporal and spatial variability of high concentrations that have been regularly registered before local flowering. The flowering pattern depends on many competing factors and varies from year to year and region to region. Concentrations, in turn, depend on several processes taking place at a wide range of scales. Various local and regional environmental drivers affect the timing of flowering and the release processes of pollen (Jato et al. 2002), while synoptic-scale atmospheric conditions affect the phenological stages over a region and also determine the transport of the emitted pollen grains from adjacent and remote regions. All these factors cause intensive and irregular temporal and spatial variations in pollen patterns from year to year. For example, in Lithuania, *Betula* contribution to the total annual pollen counts varies from 12 to 66% (Šaulienė et al. 2007), depending on the environmental factors and weather during the specific spring.

The most challenging part of the pollen season to forecast is the initial phase, during which local flowering has not yet commenced, and there can still be airborne pollen from LRT. A possible way to partly reduce the impact of this uncertainty is to define the start of the pollen season using the percentage of 2.5% threshold (cf. Fig. 1). Such a definition tends to alleviate the impact of early isolated cases, and may also lead to neglecting some LRT cases. Indeed, extensive local birch forests in Lithuania commonly produce a substantial amount of pollen during the main pollinating season, and the absolute value that corresponds to the 2.5% threshold can therefore be fairly high. However, for the data used in this study, the start of pollination season was mostly determined by the pollen, which has been transported from remote sources even according to this criterion, instead of the pollen released from local forests.

There is one specific characteristic of the considered region. In Europe, birch flowering starts in the south-western regions of the continent and gradually propagates towards the north-eastern regions (e.g. Siljamo et al. 2008a). In Lithuania, the flowering zones commonly spread partly in the opposite direction: the flowering starts in the eastern part of the country and then it is transported to the west—from Vilnius to Šiauliai and Klaipėda (cf. Fig. 1; Siljamo et al. 2008). This phenomenon is probably caused by the cooling effect of the Baltic Sea in spring. The stations of Šiauliai and Klaipėda are fairly close to each other, and the observed patterns at these two stations are in most cases similar, while the measured concentrations at the station of Vilnius are characteristically substantially different. This inverse evolution of the propagation of flowering can be related to the early cases in 2005 and 2007, when the model predictions suggested source areas to the north of the measurement sites. Taking also into account the high-pressure dominated weather conditions during the episodes, the associated light winds with variable wind directions and the small time lag with respect to the phenological start of flowering, we concluded that the sources can, in fact, be located in warm habitats in Lithuania or in its immediate vicinity. As the variability of phenological observations is high (Siljamo et al. 2008a), such observations do not necessarily detect the earliest flowering trees.

This study is related to previous corresponding investigations of Sofiev et al. (2006a), Skjøth et al. (2007), Mahura et al. (2007), Siljamo et al. (2007, 2008b) and Sofiev et al. (2008b). It has been shown that the pre-season pollen concentrations and their origins vary substantially from year to year, and it is challenging to recognise potentially occurring systematic patterns for individual countries. However, Skjøth et al. (2007), based on the analysis of 7 years from 2000 to 2006 using a Lagrangian dispersion model ACDEP (Atmospheric Chemistry and Deposition), showed that episodes of birch pollen transported from Poland and Germany influence the pre-seasonal concentrations in Denmark almost every year. Skjøth et al. (2009) have also studied birch pollen concentrations recorded at London, UK, using a combination of trajectory analysis, bi-hourly birch pollen counts and source maps to examine specific episodes. The present study contains an analysis of data for four consecutive years (the whole period of available aerobiological observations in Lithuania) and demonstrated that the spatial and temporal patterns of the LRT of early pollen towards Lithuania for the years studied seem to be more complicated compared with, e.g., those presented by Skjøth et al. (2007). The predicted source regions were similar only for some days in 2004 and 2006 (the transport from the south-easterly directions), but otherwise the sources of LRT pollen were unique each year.

Regional specifics have been found out also in other studies, but there are also some more general features. For instance, for Finland, the Baltic countries are commonly important source areas of birch pollen (Ranta et al. 2006; Sofiev et al. 2006, Siljamo et al. 2008b). In 2004, the first LRT episode in Finland was during the 14–15th of April, when source areas were located on the coastal regions of Poland and Germany (Sofiev et al. 2006, Siljamo et al. 2008b). It is noteworthy that the footprint computed for Šiauliai narrowly missed these regions (cf. Fig. 3). However, taking into account the uncertainty of its determination, these sources could also contribute to the Lithuanian LRT episode 12–14 April 2004. Later in spring, the same source areas seem to affect again both Lithuania and Finland: the high concentrations were registered at the Finnish sites a few days later than in Lithuania with the footprint spreading in the southern direction.

In 2005, there were no pollen LRT episodes in Finland. This is in agreement with the present study (cf. Fig. 7), in which the prevailing transport at the relevant times was from the north, so that Lithuania also did not receive early pollen from distant sources. During both 2006 and 2007, LRT episodes were recorded in Finland about 2 days later than the corresponding cases in Lithuania (Sofiev et al. 2008b; Siljamo et al. 2008b), which again suggested that the source regions may be partly the same.

These considerations demonstrate that the analyses of the LRT pollen should address more extensive geographical regions than most of the previously published studies do (including the current one). Such studies should also be based on more extensive observational data sets, collected in several countries. The joint analysis of their outcome could provide a better insight of the spatial and temporal distributions of the LRT episodes in Europe, compared with those in any individual regional studies.

This study also aimed at comparing the predictions obtained using various methodologies for the source apportionment. We used two versions of the SILAM modelling system, both producing the footprint maps, and the HYSPLIT backward trajectories, which are widely used for the qualitative analysis of the observations (e.g. Mahura et al. 2007; Skj  th et al. 2007). Apart from different formulations, the models were driven by substantially different meteorological data sets.

For the analysed 5-year period, we found both cases, in which the predictions of the SILAM model variants and those of HYSPLIT were similar, and cases, where they were substantially different. In general, when the meteorological conditions were straightforward to interpret, stable in time and with well-defined transport directions, the results were similar. For complicated circulation patterns, the model predictions differed more substantially. These included the presence of prevailing high-pressure systems, with associated weak wind speeds and rapid changes of the wind directions. In general, it is more challenging to forecast cases with a bifurcation of the atmospheric flow with quickly changing wind. In principle, even two (or more) branches of the footprint pattern can be recognised using adjoint modelling with a sufficiently high-resolution meteorological data. In one case (2004), such complex meteorological conditions could have resulted in

substantially inaccurate source regions predicted by the HYSPLIT model for one of the analysed days. The high-probability footprint computations using the two different dynamic modules of the SILAM model provided qualitatively similar results.

There are several possible reasons, why the HYSPLIT model did not predict the western direction of the footprint for the case considered in 2004. (1) First, the approaches based on a collection of few trajectories may encounter difficulties particularly in cases with complicated and dynamic atmospheric patterns. For instance, there would be a possibility of the western branch of the footprint based on the trajectories for 12th of April. However, the predictions for the next day firmly exclude it. (2) The results of the trajectory-based assessments can in some cases depend on the subjective selection of the details of the trajectories, such as their start times and altitudes. (3) Finally, a possible reason for missing a part of the footprint can be an insufficient resolution of the underlying meteorological data set (~ 250 km) and/or inaccuracies in the meteorological data. The horizontal spatial resolutions of the HIRLAM model (20 km) and the ECMWF model (25 km) have more than 10-fold denser grids, compared with the meteorological data used by the HYSPLIT model. The computations of this study are thus affected with these differences in the underlying data sets, which allow several interpretations of peculiarities mentioned in the result section. However, the above-mentioned general features of the trajectory models do not depend on the meteorological data.

Generally, it can be concluded that the application of more comprehensive and less subjective approaches, such as adjoint modelling, is a more reliable option than trajectory analyses for the source apportionment. This is crucial especially in the presence of prevailing high-pressure systems, with the associated light wind speeds or calm conditions, and in the presence of dynamic atmospheric developments. Such analyses critically depend on both model formulations and on the quality of the meteorological data sets used as input in the trajectory or adjoint models.

For the analysis of the most complicated cases, the more accurate delineation of the source areas requires a two-step approach. As it was demonstrated in analysis of the first episode of 2004, the computation of the footprint for zero-recording observations can

help to exclude some of the suspected source areas from the consideration. This is a useful computational technique that has not been applied in the open literature up to date for source analyses. We recommend it to be used more widely, as it can provide valuable additional insight regarding the possible source regions.

The phenological observations are important for detection of potential LRT episodes. Despite the substantial uncertainties in the phenological timing (e.g. Siljamo et al. 2008a), the abundance of the phenological information allows an evaluation of the temporal differences between pollen caught in traps and the observed onset of flowering (Kasprzyk 2003; Estrella et al. 2006; Ranta et al. 2006). If the spatial density of the phenological network is sufficient, the spatial representativity of the data can be explicitly evaluated and a probability distribution function can be determined for the onset of flowering. Even a simple determination of the earliest flowering date in comparison with the reported median can provide valuable information regarding this variability, and help to distinguish between the local and non-local pollen observed at aerobiological stations.

5 Conclusions

An analysis of potential LRT episodes in early spring in Lithuania has been performed for the period of available observations in 2004–2007, using the birch pollen counts from three aerobiological stations, phenological observations, various model computations and meteorological analyses. During this period, we found a total of 24 days, during which the observed pollen concentrations at least one of the measurement stations were possibly controlled by distant sources from different regions of Europe.

The analysis was performed in four steps. First, non-zero pollen counts before the first local flowering date were considered as candidates for the LRT episodes at each aerobiological site. Second, adjoint dispersion and backward trajectory computations were performed for each candidate episode. Third, the modelling results were inter-compared and analysed in terms of the synoptic-scale meteorological situation. Fourth, the possibility of the suggested source areas to produce pollen during the day considered was evaluated using the phenological

and aerobiological data in those areas, as well as in the light of the climatologic information.

According to the predictions of the SILAM model, the source regions for observed pollen concentrations in Lithuania during the considered episodes were located in Belarus, Ukraine and Moldova (e.g. in 2004 and 2006), in the countries of the Baltic Sea region, such as the southern regions of Sweden, Denmark, possibly northern regions of Poland and Germany, but also in the relatively warmer habitats in Lithuania (e.g. in 2005, 2007).

The analysis of data for more extensive regions than one European country can provide a better insight of the spatial and temporal features of the LRT episodes on regional and continental scales. The appropriate analysis of such cases therefore requires a sufficiently wide geographical coverage of monitoring data and modelling, preferably using several modelling techniques and input data sets.

This study also aimed at an evaluation of the predictions of source apportionment using different modelling approaches: adjoint dispersion modelling with two SILAM model variants and the HYSPLIT model isobaric backward trajectories. Clearly, the quality and spatial resolution of underlying meteorological data are crucial for the accuracy of both dispersion and trajectory modelling systems. The horizontal spatial resolutions of the HIRLAM model and the ECMWF model were more finely spaced by an order of magnitude, compared with those of the meteorological data used by the HYSPLIT model, which might have influenced the outcome of the analyses for some episodes, and complicated the comparison of the approaches.

However, based on general arguments, it can be concluded that the application of more comprehensive and less subjective approaches, such as adjoint modelling, is a more reliable option than trajectory analyses for analysing the source regions. The results of the trajectory-based assessments suffer from a limited representativeness of a single trajectory, depend on the subjective selection of the details of the trajectories, such as their start times and altitudes, while the execution of adjoint computations involves a substantially smaller number of modelling choices and covers the whole phase space of the model. This is crucial especially in dynamic situations, i.e. with strongly variable atmospheric developments.

It can therefore be recommended to involve more rigorous, albeit also more expensive, approach for computation of the footprint of the observations.

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References

- Bergamaschi, P., Krol, M., Dentener, F., Vermeulen, A., Meinhardt, F., Graul, R., et al. (2005). Inverse modelling of national and European CH₄ emissions using the atmospheric zoom model TM5. *Atmospheric Chemistry and Physics*, 5, 2431–2460.
- Cecchi, L., Torrigiani Malaspina, T., Albertini, R., Zanca, M., Ridolo, E., Usberti, I., et al. (2007). The contribution of long-distance transport to the presence of *Ambrosia* pollen in central northern Italy. *Aerobiologia*, 23, 145–151.
- Clot, B. (2001). Airborne birch pollen in Neuchâtel (Switzerland): Onset, peak and daily patterns. *Aerobiologia*, 17, 25–29.
- D'Amato, G., Cecchi, L., Bonini, S., Nunes, C., Annesi-Maesano, I., Behrendt, H., et al. (2007). Allergenic pollen and pollen allergy in Europe. *Allergy*, 62, 976–990.
- Draxler, R. R., Rolph, G. D. (2003). HYSPLIT (hybrid single-particle lagrangian integrated trajectory) Model access via NOAA ARL READY Website (<http://www.arl.noaa.gov/ready/hysplit4.html>). NOAA Air Resources Laboratory, Silver Spring, MD. Accessed September 23, 2008.
- Estrella, N., Menzel, A., Krämer, U., & Behrendt, H. (2006). Integration of flowering dates in phenology and pollen counts in aerobiology: Analysis of their spatial and temporal coherence in Germany (1992–1999). *International Journal of Biometeorology*, 51, 49–59.
- Galperin, M. (1999). Approaches for improving the numerical solution of the advection equation. In Z. Zlatev, J. Dongarra, I. Dimov, J. Brandt, & P. J. Builtjes (Eds.), *Large scale computations in air pollution modelling* (pp. 161–172). The Netherlands: Kluwer Academic Publishers.
- Galperin, M. V. (2000). The approaches to correct computation of airborne pollution advection. In: *Problems of ecological monitoring and ecosystem modelling* (Vol. XVII, pp. 54–68). St. Petersburg: Gidrometeoizdat (in Russian).
- Galperin, M., Maslyayev, A., Pekar, M. & Sofiev, M. (1996). The development of HM model in 1996. *MSC-E Report 5/96*, Moscow, July 1996, 62.
- Galperin, M., & Sofiev, M. (1998). The long-range transport of ammonia and ammonium in the Northern Hemisphere. *Atmospheric Environment*, 32(3), 373–380.
- Gassmann, I. M., & Pérez, F. C. (2006). Trajectories associated to regional and extra-regional pollen transport in the southeast of Buenos Aires province, Mar del Plata (Argentina). *International Journal of Biometeorology*, 50, 280–291.
- Goldberg, C., Buch, H., Moseholm, L., & Weeke, E. V. (1988). Airborne pollen records in Denmark, 1977–1986. *Grana*, 27, 209–217.
- Hidalgo, J. P., Mangin, A., Galán, C., Hembise, O., Vázquez, M. L., & Sanchez, O. (2002). An automated system for surveying and forecasting *Olea* pollen dispersion. *Aerobiologia*, 18, 23–31.
- Hirst, J. M. (1952). An automatic volumetric spore trap. *Annals of Applied Biology*, 39(2), 257–265.
- Jato, V., Méndez, J., Rodríguez-Rajo, J., & Seijo, C. (2002). The relationship between the flowering phenophase and airborne pollen of *Betula* in Galicia (N.W. Spain). *Aerobiologia*, 18, 55–64.
- Karpinen, A., Sofiev, M., Siljamo, P., Kukkonen, J., Ranta, H., Linkosalo, T., Jäger, S., Rasmussen, A., Nicklaß, D. & Wanner, L. (2007). Pollen: A challenge for environmental information services In O. Hryniewicz, J. Studziński & A. Szewski (Eds.), *EnviroInfo Warsaw 2007, environmental informatics and systems research* (Vol. 2, pp. 75–79): *Workshop and application papers, The 21st international conference on "informatics for environmental protection"* Warsaw, Poland. Shaker Verlag: Aachen 2007, ISBN 978-3-8322-6397-3, ISSN 1616-0886.
- Kasprzyk, I. (2003). Flowering phenology and airborne pollen grains of chosen tree taxa in Rzeszów (SE Poland). *Aerobiologia*, 19, 113–120.
- Kuparinen, A. (2006). Mechanistic models for wind dispersal. *Trends in Plant Science*, 11, 296–301.
- Kuparinen, A., Markkanen, T., Riikonen, H., & Vesala, T. (2007a). Modeling air-mediated dispersal of spores, pollen and seeds in forested areas. *Ecological modelling*, 208, 177–188.
- Kuparinen, A., Snäll, T., Vänskä, S., & O'Hara, B. R. (2007b). The role of model selection in describing stochastic ecological processes. *Oikos*, 116, 966–974.
- Laaide, M. (2001). Regional variations in the pollen season of *Betula* in Burgundy: two models for predicting the start of the pollination. *Aerobiologia*, 17, 247–254.
- Latałowa, M., Miętus, M., & Uruska, A. (2002). Seasonal variations in the atmospheric *Betula* pollen count in Gdańsk (southern Baltic coast) in relation to meteorological parameters. *Aerobiologia*, 18, 33–43.
- Mahura, G. A., Korsholm, S. U., Baklanov, A. A., & Rasmussen, A. (2007). Elevated birch pollen episodes in Denmark: Contributions from remote sources. *Aerobiologia*, 23, 171–179.
- Mandrioli, P., Comtois, P., Dominguez Vilches, E., Galan Soldevilla, C., Isard, S., & Syzdek, L. (1998). Sampling: Principles and techniques. In P. Mandrioli, P. Comtois, & V. Levizzani (Eds.), *Methods in aerobiology* (pp. 49–101). Bologna: Pitagora Editrice.
- Marchuk, G. I. (1982). *Mathematical modeling in the environmental problems*. Moscow: "Nauka" publisher. (320 pp, in Russian).

- Navasaitis, M., Ozolinčius, R., Smaliukas, D., & Balevičienė, J. (2003). *Lietuvos dendroflora*. Kaunas: Lututė. (575 pp, in Lithuanian).
- Porsbjerg, C., Rasmussen, A., & Backer, V. (2003). Airborne pollen in Nuuk, Greenland, and the importance of meteorological parameters. *Aerobiologia*, 19, 29–37.
- Prank, P., Sofiev, M., Kaasik, M., Ruuskanen, T., Kukkonen, J., & Kulmala, M. (2008). The origin and formation mechanics of aerosol during a measurement campaign in Finnish Lapland, evaluated using the regional dispersion model SILAM. In C. Borrego & A. I. Miranda (Eds.), *Air pollution modeling and its application XIX, NATO science for peace and security series-C: Environmental security* (pp. 530–538). Berlin: Springer.
- Rannik, Ü., Markkanen, T., Raittila, J., Hari, P., & Vesala, T. (2003). Turbulence statistics inside and over forest: Influence on footprint prediction. *Boundary-Layer Meteorology*, 109, 163–189.
- Ranta, H., Kubin, E., Siljamo, P., Sofiev, M., Linkosalo, T., Oksanen, A., et al. (2006). Long distance pollen transport cause problems for determining the timing of birch pollen season in Fennoscandia by using phenological observations. *Grana*, 45, 297–304.
- Saarikoski, S., Sillanpää, M., Sofiev, M., Timonen, H., Saarnio, K., Teinilä, K., et al. (2007). Chemical composition of aerosols during a major biomass burning episode over northern Europe in spring 2006: Experimental and modelling assessments. *Atmospheric Environment*, 41, 3577–3589.
- Sauliune, I., & Motiekaityte, V. (2005). Peculiarities of aeropalynological monitoring in Northern Lithuania. *The 6th international conference "environmental engineering" selected papers*, 1, 252–256.
- Šaulienė, I., & Veriankaitė, L. (2006). Application of backward air mass trajectory analysis in evaluating airborne pollen dispersion. *Journal of Environmental Engineering and Landscape Management*, XIV(3), 113–120.
- Šaulienė, I., Veriankaitė, L., & Lankauskas, A. (2007). The analysis of the impact of long distance air mass to airborne pollen concentration. *Acta Biologica Universitatis Daugavpilisensis, Suppl 1*, 61–74.
- Siljamo, P., Sofiev, M., Ranta, H., Linkosalo, T., Kubin, E., Ahas, R., et al. (2008a). Representativeness of point-wise phenological *Betula* data collected in different parts of Europe. *Global Ecology and Biogeography*, 17, 489–502.
- Siljamo, P., Sofiev, M., Severova, E., Ranta, H., Kukkonen, J., & Polevova, S. (2008b). Sources, impact and exchange of early-spring birch pollen in the Moscow region and Finland. *Aerobiologia* doi:10.1007/s10453-008-9100-8.
- Siljamo, P., Sofiev, M., Severova, E., Ranta, H. & Polevova, S. (2007). On influence of long-range transport of pollen grains onto pollinating seasons. In C. Borrego & E. Renner (Eds.), *Developments in Environmental Science*, 6. doi: 10.1016/S1474-8177(70)06074-3. *Air Pollution Modelling and its Applications XVIII*, 708–716.
- Skjøth, C. A., Smith, M., Brandt, J., & Emberlin, J. (2009). Are the birch trees in Southern England a source of *Betula* pollen for North London? *International Journal of Biometeorology*, 53, 75–86.
- Skjøth, A. C., Sommerw, J., Stachz, A., Smithz, M., & Brandt, J. (2007). The long-range transport of birch (*Betula*) pollen from Poland and Germany causes significant pre-season concentrations in Denmark. *Clinical and Experimental Allergy*, 37, 1204–1212.
- Smith, M., & Emberlin, J. (2006). A 30-day-ahead forecast model for grass pollen in north London, United Kingdom. *International Journal of Biometeorology*, 50, 233–242.
- Sofiev, M. (2000). A model for the evaluation of long-term airborne pollution transport at regional and continental scales. *Atmospheric Environment*, 34(15), 2481–2493.
- Sofiev, M. (2002). Extended resistance analogy for construction of the vertical diffusion scheme for dispersion models. *Journal of Geophysical Research—Atmosphere*, 107, D12. doi:10.1029/2001JD001233.
- Sofiev, M., Galperin, M., & Genikhovich, E. (2008a). A construction and evaluation of Eulerian dynamic core for the air quality and emergency modelling system SILAM. In C. Borrego & A. I. Miranda (Eds.), *Air pollution modeling and its application XIX. NATO science for peace and security series—C: Environmental security* (pp. 699–701). Berlin: Springer.
- Sofiev, M., Siljamo, P., Ranta, H., Linkosalo, T., Jaeger, S. & Jaeger, C. (2008b). From Russia to Iceland: An evaluation of a large-scale pollen and chemical air pollution episode during April and May, 2006. *Aerobiological Monographs*, 1 (in press).
- Sofiev, M., Siljamo, P., Ranta, H., & Rantio-Lehtimäki, A. (2006a). Towards numerical forecasting of long-range air transport of birch pollen: Theoretical considerations and a feasibility study. *International Journal of Biometeorology*, 50, 392–402.
- Sofiev, M., Siljamo, P., Valkama, I., Ilvonen, M., & Kukkonen, J. (2006b). A dispersion modelling system SILAM and its evaluation against ETEX data. *Atmospheric Environment*, 40, 674–685.
- Undén, P., Rontu, L., Järvinen, H., Lynch, P., Calvo, J. & Cats, G. et al. (2002). *HIRLAM-5 scientific documentation*. December 2002. SMHI: Norköping, Sweden.
- Van de Water, K. P., & Levetin, E. (2001). Contribution of upwind pollen sources to the characterization of *Juniperus ashei* phenology. *Grana*, 40, 133–141.
- Vogel, H., Pauling, A., & Vogel, B. (2008). Numerical simulation of birch pollen dispersion with an operational weather forecast system. *International Journal of Biometeorology*, 52, 805–814. doi:10.1007/s00484-008-0174-3.
- WHO. (2003). *Phenology and human health: Allergic disorders*. WHO Regional Office for Europe: Copenhagen. 55 pp.