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ORIGINAL ARTICLE

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Towards numerical forecasting of long-range air transport of birch pollen: theoretical considerations and a feasibility study

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Abstract This paper considers the feasibility of numerical simulation of large-scale atmospheric transport of allergenic pollen. It is shown that at least small grains, such as birch pollen, can stay in the air for a few days, which leads to a characteristic scale for their transport of ~10^3 km. The analytical consideration confirmed the applicability of existing dispersion models to the pollen transport task and provided some reference parameterizations of the key processes, including dry and wet deposition. The results were applied to the Finnish Emergency Dispersion Modelling System (SILAM), which was then used to analyze pollen transport to Finland during spring time in 2002–2004. Solutions of the inverse problems (source apportionment) showed that the main source areas, from which the birch flowering can affect Finnish territory, are the Baltic States, Russia, Germany, Poland, and Sweden—depending on the particular meteorological situation. Actual forecasting of pollen dispersion required a birch forest map of Europe and a unified European model for birch flowering, both of which were nonexistent before this study. A map was compiled from the national forest inventories of Western Europe and satellite images of broadleaf forests. The flowering model was based on the mean climatological dates for the onset of birch forests rather than conditions of any specific year. Utilization of probability forecasting somewhat alleviated the problem, but the development of a European-wide flowering model remains the main obstacle for real-time forecasting of large-scale pollen distribution.

Keywords Birch pollen · Pollen transport · Pollen forecast · Atmospheric pollution transport

Introduction

Pollen is a common cause of allergy-related diseases such as asthma, rhinitis, and atopic eczema. In the industrialized countries of central and northern Europe, up to 15% of the population is sensitive to pollen allergens, the figures being largest among children and adolescents (WHO 2003). It is generally accepted that most pollen registered by observational networks comes from local sources (Keynan et al. 1991; Rantio-Lehtimäki 1994; Campbell et al. 1999; Adams-Groom et al. 2002). Consequently, forecasts of pollen concentrations are mainly based on in situ aerobiological monitoring and phenological observations (Frøsig and Rasmussen (2003); Severova and Polevova (1996); Porsbjerg et al. (2003); Rantio-Lehtimäki and Matikainen (2002), http://www.polleninfo.org, http://www.allergology.ru). However, there is convincing evidence that the long-range transport of pollen from distant regions can significantly modify pollinating seasons (i.e., the start time and duration of high atmospheric pollen concentrations) in many European regions. This is particularly important for northern Europe and especially for Finland, where flowering takes place later in the spring. The example in Fig. 1 shows birch pollen counts in Finland in April 1999, which exceeded 2,000 and 3,000 pollen grains/m^{-3} in Turku and Oulu, respectively. This episode happened 1 month earlier than local birch flushing was recorded by the phenological network of the Finnish Forest Research Institute. Similar episodes of long-range transport of pollen are regularly registered by aerobiological networks (Corden et al. 2002; Małgorzata et al. 2002; Hjelmroos 1992; Damialis et al. 2004).

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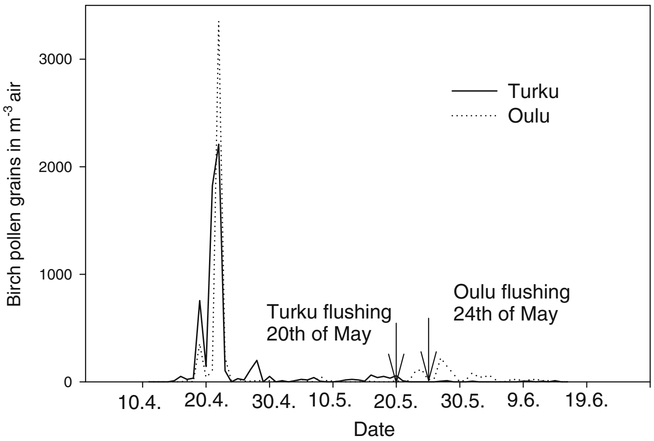


Fig. 1 Atmospheric birch pollen counts observed in Turku (southern Finland) and in Oulu (northern Finland) in spring 1999

Large-scale transport episodes cannot be predicted using only local or regional observations. Forecasting such episodes requires proper treatment of both the biological and meteorological mechanisms that control pollen release to the atmosphere and the subsequent dispersion of this pollen over the whole of Europe. Such a task can only be addressed via the use of an emission model predicting pollen flux into the air coupled with an atmospheric dispersion model, the latter driven by the fields from a numerical weather prediction model. In turn, determination of the pollen emission flux requires information on forest areas and flowering timing, duration, and intensity.

During dispersion, atmospheric pollutants, such as pollen, are subject to several processes: transport with air masses, turbulent mixing, dry and wet deposition, and chemical and physical transformations. Intensity, importance, and nature of these processes depend on the pollutant type and the form that they can take in the atmosphere. Depending on the pollutant's features and the scale of its transport, different types of models should be used for simulation of the dispersion.

In the current paper, we present the results of a feasibility study, which included analytical consideration of the features of pollen grains using birch pollen as an example, estimation of the characteristic scales of their atmospheric dispersion, preliminary error analysis, and checking the applicability of existing modelling approaches to its simulation. We also took a first glance at possible parameterizations of related processes. Finally, the paper presents the computation results for several high-concentration episodes in Finland during the springs of 2002–2004 that happened before local flowering, delineation of the source areas responsible for these episodes, and a real-time trial forecasting of such episodes performed during the spring of 2004.

Pollen grain as an atmospheric pollutant

The large size of pollen grains, some 5–50 times larger in linear dimensions than conventional atmospheric aerosols, raises a whole set of questions related to the applicability of existing atmospheric dispersion models to the evaluation of pollen transport and deposition. There are several ways to check the assumptions underlying virtually all dispersion models. Here we use the Navier-Stokes equation as the basis for such an analysis. In its general form, the Navier-Stokes equation that describes the motion of a small volume of air (or liquid) can be written as follows:

$$\frac{\partial\overrightarrow{\nu}}{\partial t}+\left(\overrightarrow{\nu}\nabla\right)\overrightarrow{\nu}=-\frac{1}{\rho}grad\,p+\frac{\eta}{\rho}\Delta\overrightarrow{\nu} \tag{1}$$

where $\overrightarrow{\nu}$ is a velocity of the volume of air (Lagrangian velocity), ρ is air density, p is pressure, and η is the dynamical viscosity (a typical value for air: η_{air}=1.8 10^{-5} kg s^{-1} m^{-1}). For slow laminar motion in the (pseudo-)stationary case, one may write:

$$\eta\Delta\overrightarrow{\nu}-grad\,p=0 \tag{2}$$

Here the stationary condition is $\partial\nu_i/\partial t=0$ and slow motion means that the Reynolds number is small, i.e., $Re=\left|\overrightarrow{\nu}\right|d/\nu\ll 1$, where d is a linear dimension (diameter) of the moving object and $\nu=\eta/\rho$ is the kinematical viscosity.

From Eqs. 1 and 2, it can be shown that the total force applied to a spherical object moving through the air is:

$$F_{Strokes}=6\pi r\eta u\left(1+\frac{3ru}{8\nu}\right) \tag{3}$$

where r is a radius of the sphere and u is its velocity relative to the surrounding air. The correction term in brackets is small when $Re\ll 1$.

Using the above equations and the physical characteristics of pollen grains, one can quantify their behavior in an atmospheric flow and evaluate the applicability of existing dispersion modeling approaches to this type of pollutant.

Transport with air masses

A key assumption in all dispersion models is that the pollutant is transported together with the air mass and follows the airflow, including small turbulent eddies, which means that its inertia is negligible. To check this assumption, it is enough to estimate the relaxation time and distance of the pollen grain in air and compare them with characteristic scales in the troposphere. Below we use the parameters of birch pollen because: (1) most allergic people are sensitive to birch, (2) it is one of the furthest-transported type of pollen grain, and (3) its shape is almost spherical, which considerably simplifies the analysis. However, the methodology is applicable for other species, too, as long as the shape-related correction terms are taken into account.

If a particle enters an airflow with its own velocity different from that of the surrounding air, it is forced to follow the main movement with a force represented by Eq. 3. Therefore, its nonstationary motion relative to the surrounding air will be described by the following equation (the *x*-axis is directed along the relative velocity vector, which reduces the problem to a one-dimensional one):

$$m\frac{d\nu}{dt} = -F_{Strokes} = -3\pi\ d\ \eta u \tag{4}$$

where *m* is the mass of the particle. The relaxation time τ for birch pollen will then be:

$$\tau = \frac{d^2\rho_{part}}{18\eta} \sim 10^{-3}\ \mathrm{sec} \tag{5}$$

Here we have used as a characteristic density of birch pollen $\rho_{part}=800\ kg\ m^{-3}$ and diameter $d=22\ \mu m$. Assuming a velocity fluctuation scale of 1 m s^{-1}, one can see that the grain inertia results in a relaxation distance of ~1 mm, the characteristic path, after which the grain motion has become adjusted to that of the surrounding air. Therefore, for velocity gradients smaller than 1 m s^{-1} mm^{-1}, the grain can be considered as noninertial. Since in the real atmosphere the gradients are much smaller, this assumption seems to be well fulfilled. The only comparable spatial scale is the near-surface laminar layer, which can be about 1-mm thick. However, near the surface, the intensity of turbulence decreases, together with small-scale velocity variations, which means that even this layer cannot be penetrated by the pollen grains due to their inertia.

The above semiqualitative analysis shows that: (1) for typical atmospheric conditions, the pollen particles (at least birch pollen) do follow the air flows, including turbulent eddies; (2) inertia of grains is also insufficient to penetrate the near-surface laminar layer. Therefore, pollen transport in the atmosphere can be treated via existing advection–diffusion and deposition schemes, which entirely neglect the inertia of the transported species. In addition, the above equations allow straightforward evaluation of dry deposition fluxes, as shown below.

Dry deposition evaluation

The classical scheme for the near-surface dry deposition fluxes includes at least two parallel chains of resistances: one represents gravitational settling; the other consists of aerodynamic, molecular diffusion and surface resistances. Despite the inherently self-contradicting definition of gravitational resistance, this scheme can be used (with certain care) to estimate the relative importance of the fluxes through both chains. Considering the stationary motion of a grain due to gravitational force, from Eq. 3 one can derive:

$$u = \frac{g\rho_{part}d^2}{18\eta} \tag{6}$$

where *g* is gravitational acceleration. The two assumptions behind this formula are: (1) that the correction term in Eq. 3 is small: $\frac{3ru}{8\nu} \ll 1$, and (2), the Reynolds number is small $Re \ll 1$. For birch grains, these assumptions are fulfilled:

$$u \sim 1.2\ cm/s; \quad \frac{3du}{16\nu} \sim 3.2 \cdot 10^{-3};\ Re \sim 1.7 \cdot 10^{-2} \tag{7}$$

The gravitational resistance is the inverse of the settling velocity:

$$R_{grav} = 1/u \sim 85\ s\ m^{-1} \tag{8}$$

The aerodynamic resistance R_A is independent of particle features and has typical values of $1\text{–}100\ s\ cm^{-1}$, depending on the efficiency of the turbulence. The surface resistance for particles is usually assumed to be zero, which is quite reasonable for the case of pollen grains. The laminar layer resistance R_B, representing the process of diffusion through the near-surface thin laminar sublayer is usually computed as:

$$R_B = \frac{2}{\kappa u*}\left(\frac{Sc}{\mathrm{Pr}}\right)^{2/3}, \quad Sc = \nu/D \tag{9}$$

where $u*$ is a friction velocity, κ=0.4 is the von Karman constant, Pr=0.72 is the Prandtl number, and Sc is the Schmidt number. The diffusivity D of the grain due to molecular-scale processes can be computed from Brownian diffusion and the Einstein formula that connects D with kinematical Navier-Stokes considerations ($k=1.38\ 10^{-23}\ J\ K^{-1}$, the Stefan-Boltzman constant):

$$D = \frac{kT}{3\pi d\eta}, \tag{10}$$

where *T* is the temperature of the air. For birch pollen, we get:

$$D \sim 10^{-12}m^2s^{-1};\ R_B \sim 3.5\ 10^5\ s\ m^{-1}. \tag{11}$$

Comparison of these values and the gravitational settling velocity shows that diffusion plays a negligible role in (birch) pollen dry deposition from the atmosphere. Since the laminar layer also cannot be penetrated by grains due to their inertia (see above), the overall dry deposition velocity for birch pollen will be about 1 cm s^{-1}. This estimate is comparable with the values for “classical” long-range transported species and corresponds to half-lifetime of ~1 day in the atmosphere due to dry deposition. This implies that about half of the emitted mass will be transported over a distance >10^3 km. In reality, part of the grains can stay in the atmosphere considerably longer due to turbulent vertical mixing, which will oppose the downward motion. A more experimental approach to the estimation of the

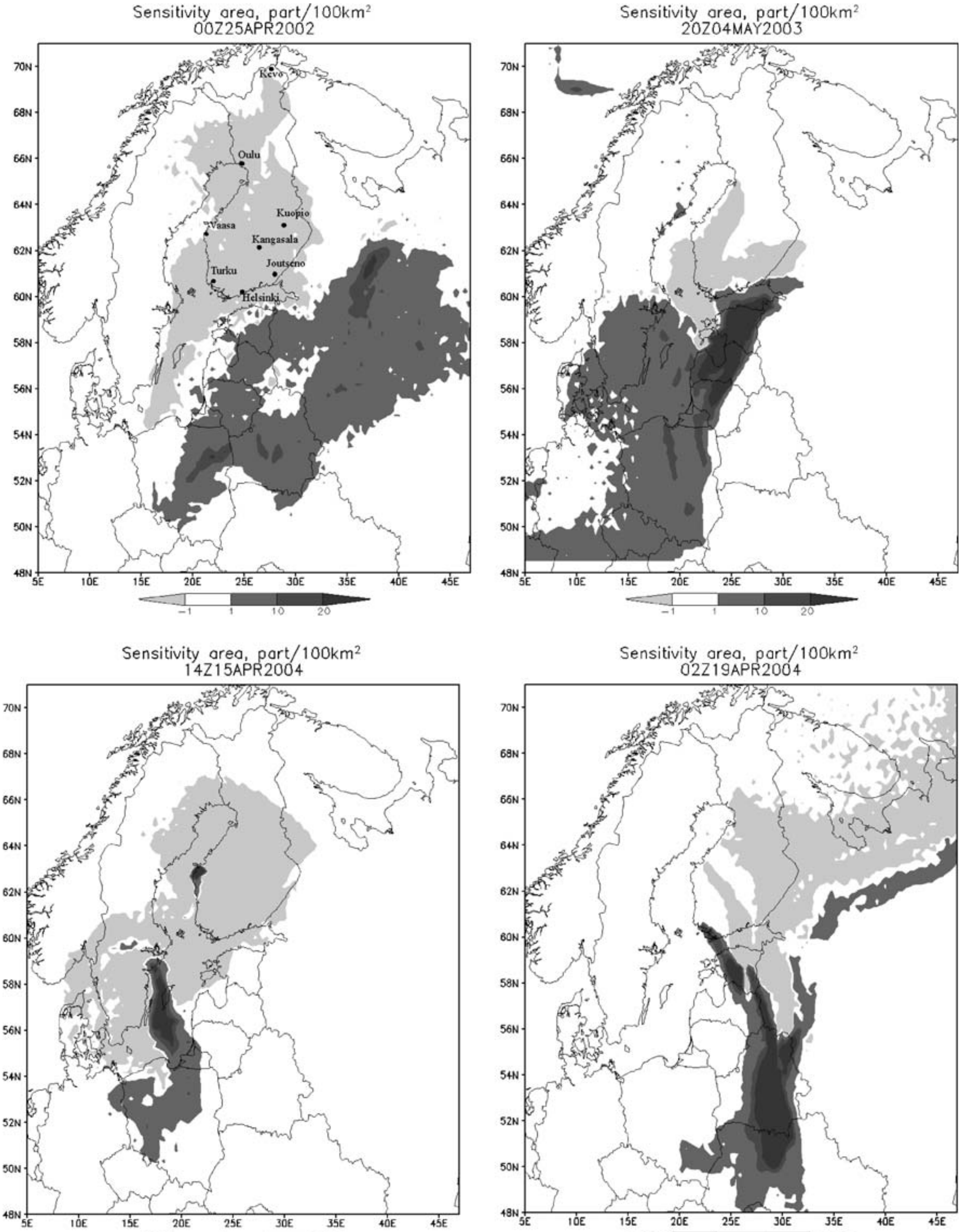


Fig. 2 Delineation of source areas that created the observed pollen counts registered by Finland aerobiological network (sites are marked at panel **a**) for the episodes: **a** 25 April 2002, **b** 4 May 2003, **c** 15 April 2004, **d** 19 April 2004. *Dark-grey areas* outline the regions where sources causing the corresponding episode can be located; *light-grey areas* show regions with the most probable zero pollen emission flux during the episodes

settling velocity of corn pollen can be found in Aylor (2002) and, in applications to other species, in Helbig et al. (2004).

Wet deposition processes

The parameterization of wet deposition has to rely on empirical approaches. Models describing the kinetics of scavenging by precipitation are too complicated and uncertain to be applied in three-dimensional (3D) models. Usually, parameterization via a scavenging coefficient Λ is used, where Λ depends on the macrofeatures of precipitation such as: precipitation intensity, rain versus snow, convective versus large-scale, in-cloud versus subcloud scavenging, etc. Such an approach relies on direct measurements of the scavenging coefficient, which are nonexistent for pollen grains. However, most types of pollen exhibit a hydrophobic behavior, which reduces the importance of in-cloud processes. The remaining process of subcloud scavenging occurs due to mechanical collisions of the grains and falling droplets. This mechanism was well studied in the classical work of Chamberlain (1953). In the present study, however, we used the standard scavenging model of the Finnish Emergency Dispersion Modelling System (SILAM), which is based on observations from wet deposition of the broad-size spectrum aerosol originating from the Chernobyl release (Anttila et al. 1987; Horn et al. 1987; Smith and Clark 1989; Jylhä 1991). This model distinguishes in- and subcloud scavenging and, despite a possible underestimation of pollen scavenging intensity, provides accuracy sufficient for the needs of a feasibility study. The implementation and a full-scale validation of the Chamberlain impact scheme were left for future studies. The above considerations justify the use of common dispersion mechanisms to describe pollen grain transport and deposition in the troposphere. The errors introduced are smaller than those generated by uncertain meteorological parameters and emission source terms.

Configuration of SILAM model for pollen dispersion simulations

The findings and parameterizations described above were introduced into the Finnish emergency modeling system SILAM (Sofiev and Siljamo 2003; Siljamo et al. 2004), which was then used to study the impact of the long-range transport of birch pollen to Finland. We considered two types of the simulations, which required specific model configuration and input data: the source apportionment task (often called as an "inverse dispersion problem") and the task of forecasting the pollen episodes due to long-range transport.

Source apportionment (inverse) problem for pollen episodes recorded in Finland

In order to better understand the scale and impact of long-range pollen grain transport to Finland, we considered several cases in which high pollen concentrations were observed prior to local flowering and delineated the specific territories from where the grains came. For source delineation, we used adjoint dispersion simulations with the SILAM model (see Sofiev and Siljamo (2003) and Sofiev and Atlaskin (2004) for details). These were based on several years of early pollen counts registered by Finnish aerobiological stations (Fig. 2a). These observations were treated as a "sensitivity source term," thus providing the model input. The output fields outlined the areas from which the observed grains can originate (dark-grey-shadowed areas), as well as those where sources cannot be located (light grey). White areas did not affect the stations, so the probability of these sources being there is small.

Forecasting the pollen episodes due to long-range transport

Forward simulation of pollen transport (for both past events and forecasts) requires definition of the emission flux or some other means of initiating pollen concentrations in the modeled domain. All approaches would require a European-wide birch forest map as an underlying data set, something that appeared to be nonexistent until this study. Therefore, our first task was to compile this map from available information.

Birch-forest map

The most detailed data set for Europe contains information on 115 different tree species on a 1-km×1-km grid (Köbler and Seufert 2001); it also includes *Betula pendula* and *Betula pubescens*. Köbler and Seufert (2001) based the spatial distribution of the forest area on the COoRdinate INformation on the Environment (CORINE) (CEC 1994) land-cover data set and the Pan-European Land Cover Mapping (PELCOM) project (Mücher 2000). Tree species information came from the measurement network of the transnational survey (ICP Forest Level I) of forest condition in Europe (UN-ECE 1998). However, the maps only cover western and central Europe and do not contain information concerning eastern countries, including Russia. The maps also reveal irregularities, probably related to the specifics of national methodologies for forest surveys. A complementary data set came from the European Forest Institute (EFI). These maps are a combination of National Oceanic and Atmospheric Administration –Advanced Very

High Resolution Radiometer (NOAA-AVHRR) data and forest inventory statistics (Schuck et al. 2002; Päivinen et al. 2001). Unfortunately, these data sets only recognize coniferous, broadleaf, and mixed forests without any species delineation.

When combining these data sets, we used Köbler's and Seufert's (2001) data for Western Europe and Scandinavia and ignored inconsistent data in Estonia, Denmark, and the UK. These countries reported unreasonably small or no birch fractions in their broadleaf forests. Gaps in the resulting map and a "white space" over the Commonwealth of Independent States (CIS) countries were filled by region-wise extrapolation using the EFI broadleaf forest map as a surrogate and a characteristic fraction of birch in such a forest in the nearest western country located at the same latitude. It was assumed that north of 65°N, the broadleaf forest contains mainly birches. Between 62°N and 65°N the fraction of birch was expected to be equal to that found in Finland (80%). A fraction of 64% was used down to 57°N and then 40% and 5% down to 52°N and 47°N, respectively. The result is shown in Fig. 3.

In the following applications, the lack of quantitative information concerning the geographical distribution of individual birch species did not allow their separate consideration. The birch species were therefore mixed into a "general birch" class with the appropriate averaging of their characteristics.

Evaluation of pollen emission timing and intensity

One of the most difficult problems in pollen-dispersion forecasting is to evaluate the emission flux of grains and its time evolution. The system for trial forecasts during spring 2004 used a "climatologic" emission term, which was based on the results of long-term mean observed birch flowering dates. We applied the European flowering start and duration maps from the International Phenological Garden Project (IPG 2004). The maps were compiled by Rötzer and Chmielewski (2001) using multilinear regression analysis of phenological observations in Europe over 35 years (1961–1998).

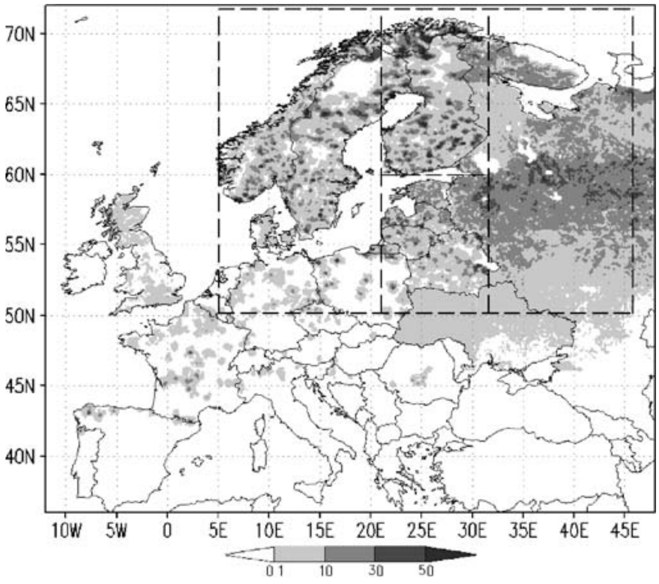


Fig. 3 The birch forest map compiled during the study. Unit=[%]. *Dashed-line rectangles* define the forest areas further referred to as western, southern, eastern, and Finnish local-source regions

Results of the model computations

This section presents the results of the above-described source apportionment and forecasting simulations in application to birch pollen episodes in Finland.

Delineation of pollen sources affecting Finland

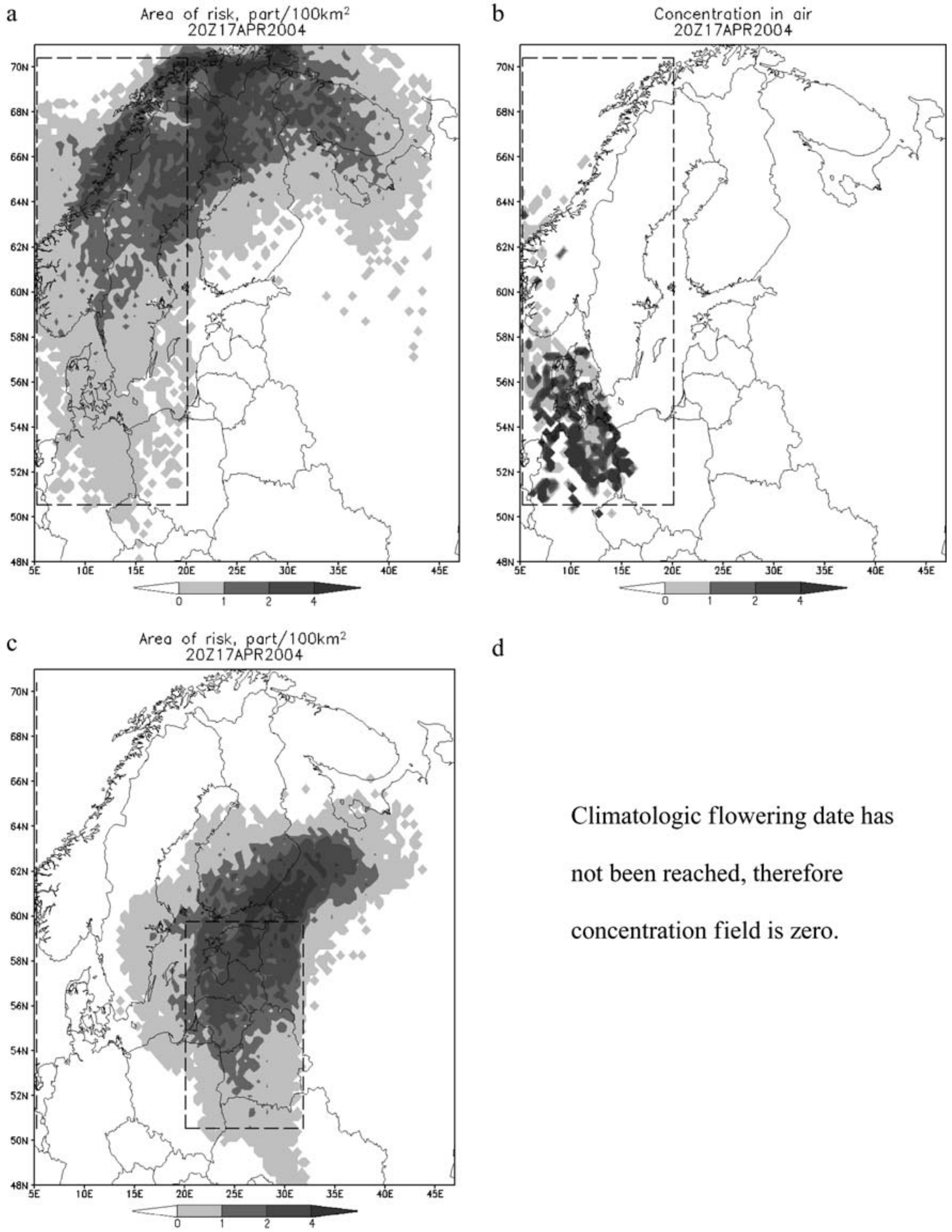
Figure 2 presents the possible source areas during the spring of 2002, 2003, and 2004 (two independent cases). It should be kept in mind that, according to the formulations of the adjoint dispersion equation, the results only outline areas that could affect corresponding measurement locations but do not say exactly where the sources of the observed concentrations are located. Therefore, all that can be stated is that the sources lie in the dark-grey-shadowed areas contrary to the white and the light-grey areas. A full-scale solution of the inverse problem, such as that of Sofiev and Atlaskin (2004), was not feasible due to a lack of observation. However, more accurate source localization may be obtained by masking the fields in Fig. 2 with a birch forest map.

The Baltic countries seem to be important source areas in almost all cases, except for the first episode in the spring of 2004 (Fig. 2). That particular episode was early in the spring; therefore, the birch had not yet flowered in the Baltic countries, making Poland the most probable source area. In the other cases, northern Germany and southern Sweden, as well as Belarus and northwest Russia, served as sources, depending on meteorological conditions.

Examples of forecasting simulations for the year 2004

During the trial semioperational simulations in 2004, the SILAM model was run once a day, providing forecasted fields of both risk areas (probabilities) and pollen concentrations for the next 48 h. Recalling the source delineation results, we split the forest map into four areas covering Finland itself and forests to the west, south, and east of it (Fig. 3, dashed-line rectangles).

A specific feature of the 2004 spring period was the early flowering time in Europe about 2 weeks before the long-term average. As a result, application of the climatologic flowering time to estimation of the onset of pollen emission failed. The maps of flowering did not show any emission flux around Finland on these days, which made the predicted pollen concentrations nearly zero and useless (Fig. 4b,d).

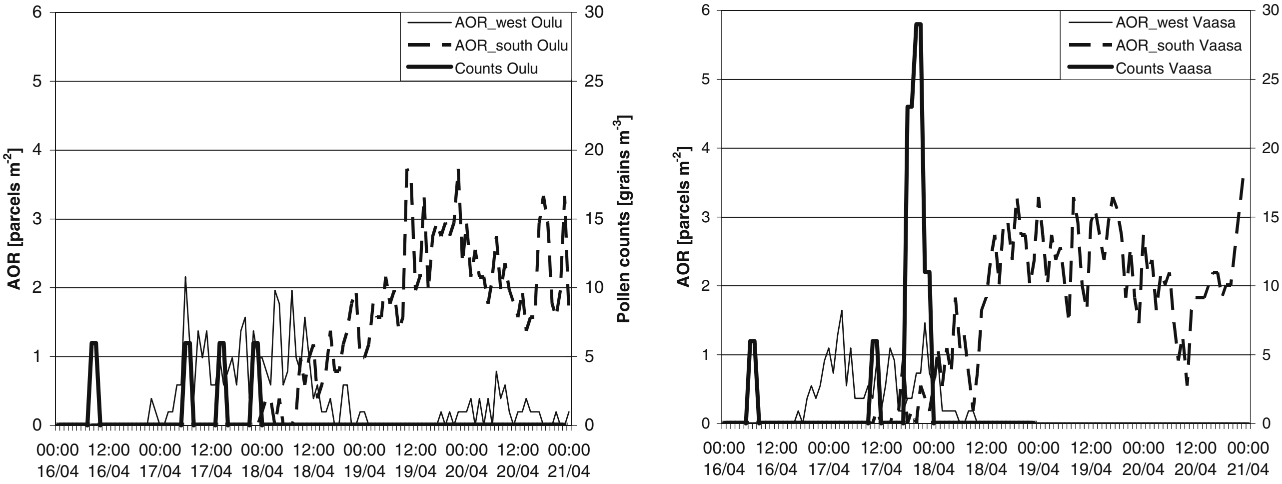


Climatologic flowering date has not been reached, therefore concentration field is zero.

Fig. 4 Forecasts for pollen episode 18 April 2004. Affected area [area of risk, *left-hand panels*, unit: (number of air parcels m^{-2})] and vertically integrated pollen concentration [*right-hand panels*, (mass-unit m^{-2})] for the western (*upper panels*) and for the southern (*lower panels*) birch forests. Source areas are delineated in Fig. 3, Emission: climatologic flowering dates, unit intensity during flowering

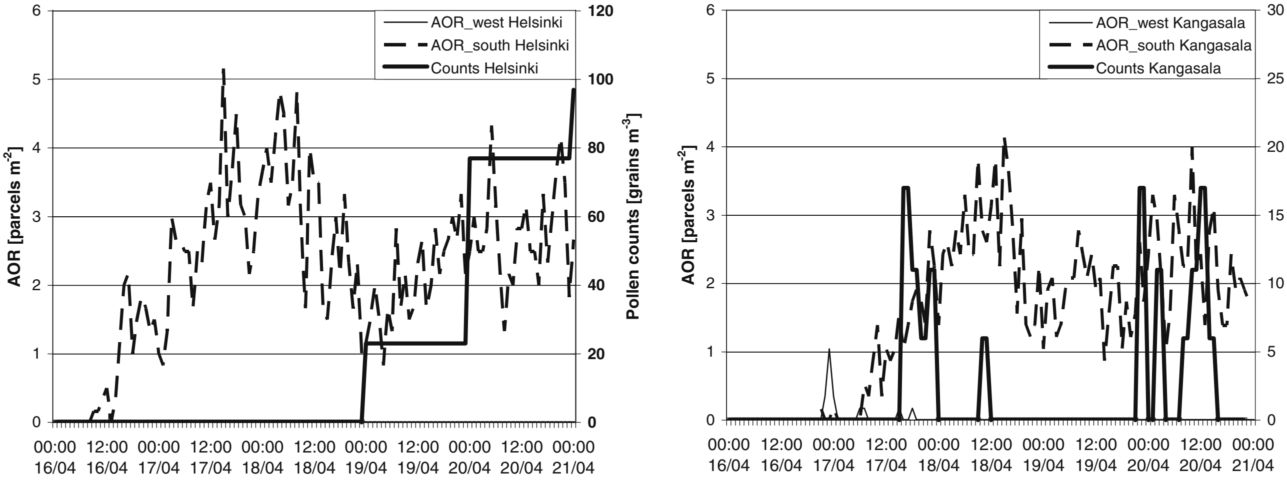
Actual pollen counts at Turku, Kangasala, and Oulu sites were nonzero as early as 17 April 2004. The peak lasted for 1 or 2 days, and by 19 April 2004, the concentrations were again small. The second rise in Helsinki, Kangasala, and Turku, with counts up to 120 grains/m^{-3}, was observed during 20–21 April 2004 (Fig. 5).

A way to make use of the model forecasts for analysis and prediction of pollen transport in 2004 was to consider the probability computations made by SILAM. With this



a Oulu (northern Finland)

b Vaasa (north-western Finland)



c Helsinki (southern Finland) Obs. scale!

d Kangasala (central Finland)

Fig. 5 Comparison of observed pollen counts (April 2004) and simulated probability [expressed via area of risk (AOR)] for the monitoring sites to be affected by western (*grey lines*) and southern (*solid black lines*) pollen source areas

approach, the model is not aimed at absolute pollen concentrations but, rather, it computes the probabilities for a given birch forest to affect receptor territories (Fig. 4a,c). The forest is considered as a constant-in-time source of a passive tracer representing air parcels that might (or might not) contain pollen. The vertically integrated concentration of such a tracer is proportional to probability for the area to be affected by the corresponding source. Therefore, this model output variable is known as area of risk (AOR). With the AOR fields as the basic model output, the pollen forecast becomes a semimanual procedure that involves an evaluation (possibly qualitative) of the state of forests in areas that affect the receptors in question. Should the flowering have started, the computed probabilities represent the actual concentration distribution (the time variation of the emission flux is skipped, however), otherwise, they are just clean air parcels.

An application of this probabilistic approach based on AOR fields appeared to be much more successful for the spring in 2004. Two examples of AOR distributions are shown in Fig. 4a,c for 20 April. The AOR time series covering both peaks during 17–21 April are depicted for the specific observation sites in Fig. 5. It is seen that the first episode was caused exclusively by western sources and mainly affected the northern part of Finland (Fig. 5). Since the pollinating areas located in Denmark and Germany were far from the receptor sites, absolute levels of concentrations were comparably low. This is in good agreement with the small AOR values. The more south-western site at Vaasa (Fig. 5b) was closer to the flowering forests, so it received more pollen. Flowering seasons in Sweden and Norway had not yet started.

The second peak, around 20 April, was caused by mainly southern sources, which affect southern and central Finland (Figs. 4c, 5c,d). Northern Finland was still under influence of the nonflowering northern forests of Norway and Sweden (Fig. 4a), so the corresponding AOR parcels were not carrying pollen. Since the southern sources are comparably close to Finland, concentrations at Kangasala and, especially, at Helsinki were much higher than those observed during previous days. An interesting conclusion can be drawn from the chart in Fig. 5c. During the whole period, the Helsinki site was under the sole influence of southern sources while the counts got elevated only after 19 April. Therefore, this date shows the start of pollination at the source areas, with a correction for 1 or 2 days of travel time.

Summarizing, both the inverse (source apportionment) and forward (forecasting) simulations showed good results, being surprisingly coherent with available (though admittedly scarce) observational information.

Discussion

The general attitude towards coarse atmospheric aerosols is that its influence is primarily local or, at most, regional. However, this study shows that from the point of view of atmospheric dispersion modeling, birch pollen grains resemble the behavior of anthropogenic aerosols with a diameter smaller than 10 μm (PM 10), (Torseth 2004; EMEP 2004). In particular, pollen has a similar gravitational settling velocity close to 1 cm s^{-1}. A general explanation for this similarity (although pollen is more than twice the size) is that pollen is a low-density particle, which makes it more susceptible to air currents and drastically reduces gravitational settling.

There are also several important differences, however, that bring birch pollen grains into the class of large-scale transported pollutants. Firstly, the grains are hydrophobic, which significantly reduces the intensity of both in-cloud processes and subcloud scavenging – by far the most intensive sinks of atmospheric aerosol. Secondly, anthropogenic pollutants with concentration levels of 5–10% near the source are often negligible, or at least do not represent a major problem. In the case of pollen, the opposite situation occurs: concentrations of 100 grains m^{-3} are considered "high" while the near-source levels are typically an order of magnitude greater. Therefore, even if dilution and removal of pollen during transport reaches 90%, the remaining amount is still considered significant enough to cause health problems. Thirdly, birch forests are abundant over large areas of Europe, thus representing a uniquely extensive source area, comparable only with that of NH_3, a typical regional pollutant in the list of large-scale ones, partly due to its huge source areas. Finally, pollen emission takes place under conditions that favor large-scale distribution: sunny days in late spring, no precipitation, moderate wind, and an emission height of more than 10 m. These conditions lead to a quick mixing of the emitted mass over a deep layer due to turbulence. All the above-mentioned factors induce a large-scale dispersion of pollen and confirm at a qualitative level the conclusions derived from formal computations of pollen behavior based on the physical characteristics of the grain. The above factors are reasonably well reproduced by existing meteorological and dispersion models, therefore simplifying their application to pollen dispersion simulations.

Since long-range transport of pollen is episodic, it is possible to formulate the inverse dispersion problem in order to delineate source areas responsible for each specific episode or even a single concentration. Solution of such a problem does not require knowledge of the source term. Therefore, it is quite straightforward, as demonstrated by the SILAM applications. Source delineation study results show the large variety of situations (Fig. 2), stress their episodic character, and hint at the limitations in the use of climatological approach for the actual forecasting of such episodes. A typical spatial scale for the problem was confirmed to be about 10^3 km with a characteristic timescale of 2–4 days.

Direct computations of pollen transport appeared to be much more difficult, because they require a sufficient knowledge of the emission term, information that is practically absent. A problem with the European birch forest map was dealt with by combining the available materials from national forest inventories and satellite images. A simple extrapolation of some characteristics that were believed to be stable (such as the fraction of birch trees in a broadleaf forest within a single climatic zone) connected these two sets into a unified map.

The resulting data set (Fig. 3), although a step forward, is not ideal. Firstly, we corrected only the most evident errors in the data sets for a few countries, but political borders are still seen in several cases. It is not clear whether they reflect differences in the forest inventory methods or in national forest policies, which might also account for the different speciation. Secondly, the extrapolation of the birch fraction of European broadleaf forests eastward contains some inherent uncertainties, such as: (1) climatic zones that do not exactly follow latitude, thus making the extrapolated birch fraction not constant; and (2) forest policy that is different in Europe and in the CIS countries. However, the use of satellite pictures largely corrects these inaccuracies because they distinguish between coniferous and broadleaf forests. The authors are aware of only one survey of Russian forests, which covers the northwestern part of Russia (Pisarenko et al. 2001), but it compares well with our map for this region.

Considerably more difficult to tackle is the problem of pollen emission parameterization. As shown in the trial forecasts for 2004, long-term averages may not be representative for a specific year. Approaches relying on information on the real-time situation can be grouped into two classes:

– The "dynamic phenological emission" approach, which is based on empirical phenological models that compute the timing and intensity of flowering using historical and real-time meteorological parameters and previous-year flowering characteristics. There are several empirical models for the evaluation of flowering start time: various heat sums (Hänninen 1990;

Linkosalo 2000a,b; Luomajoki 1999; Sarvas 1972) and more sophisticated models, such as the promoter–inhibitor approach of Schaber and Badeck (2003).
- The "emission data assimilation" approach relies on real-time observations (satellite-born or in situ) of the phenological processes. An example of satellite products that might be used is shown by Høgda et al. (2002). Another option is assimilating the real-time observed pollen concentrations directly into a dispersion model or using them to find information about grain sources—as in Sofiev and Atlaskin (2004).

So far, it is difficult to say in what form these methods will be most effective. Each has strong and weak points, and none is ready for an immediate European-wide application, mainly due to the strongly regional and empirical character of all the above models. Their generalization for the whole of Europe is not straightforward. Computation of the emission source term thus remains the most challenging part of the pollen forecasting problem. A way to avoid this obstacle might be to stress the probabilistic computations, either an AOR type as was used in the current study, or ensembles of forecasts with perturbed source parameters. As mentioned above, the first trial of this approach was already considerably more successful than the "classical" deterministic computation of concentrations.

Conclusions

The long-range atmospheric transport of natural allergens is a potential cause of difficult-to-forecast events of high concentrations of allergens in the atmosphere of the Nordic countries, which can happen weeks before the local flowering season. The most important species in this regard is the highly allergenic birch pollen, the characteristics of which favor large-scale atmospheric transport. Short-term forecasting of early peaks of pollen concentration can be addressed using a combination of existing atmospheric dispersion and biological models. From the point of view of atmospheric dispersion, (birch) pollen resembles the features of PM 10 aerosol but probably has lower scavenging efficiency. A source delineation analysis during the spring of 2002–2004 used adjoint runs of the SILAM dispersion model to show source areas affecting Finnish territory vary significantly from year to year. However, in almost all cases, forests of the Baltic countries were indicated as possible source areas. Other important regions were Russia, Poland, Germany, and southern Sweden, but their influence was much more dependent on meteorological conditions. Direct simulation of the pollen dispersion required the compilation of a birch forest map of Europe, which was made as a byproduct of the current study. Parameterization of pollen emission, especially its time variation, was difficult. The climatological approach did not show good performance due to the strong year-to-year variations of actual conditions. A workaround was the computation of probabilities for specific source areas to affect the downwind receptor territory (AOR). Detached from the uncertain emission term, results of such runs proved to be useful information in actual forecasting of pollinating episodes caused by long-range transport.

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