

Numerical simulation of birch pollen dispersion with an operational weather forecast system

Heike Vogel · Andreas Pauling · Bernhard Vogel

Received: 11 March 2008 / Accepted: 16 June 2008 / Published online: 24 July 2008
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Abstract We included a parameterisation of the emissions of pollen grains into the comprehensive model system COSMO-ART. In addition, a detailed density distribution of birch trees within Switzerland was derived. Based on these new developments, we carried out numerical simulations of the dispersion of pollen grains for an episode that occurred in April 2006 over Switzerland and the adjacent regions. Since COSMO-ART is based on the operational forecast model of the German Weather Service, we are presenting a feasibility study of daily pollen forecast based on methods which have been developed during the last two decades for the treatment of anthropogenic aerosol. A comparison of the model results and very detailed pollen counts documents the current possibilities and the shortcomings of the method and gives hints for necessary improvements.

Keywords Pollen dispersion · Numerical modelling · Operational pollen forecast

Introduction

The transport and turbulent diffusion of pollen is of great interest mainly in two fields. Firstly, pollen causes allergenic reactions (hay fever) for human beings. About

15% of the population in Europe suffers from hay fever (WHO 2003). To minimise the symptoms, allergy patients therefore need to know when and where there will be high pollen concentrations. Secondly, increasing genetic manipulation of plants leads to the problem of cross pollination. To ensure purity of plants in the vicinity of genetically modified plants, exact knowledge of the distances that can be travelled by pollen grains is required for different plant species.

During the last two decades, very sophisticated numerical models have been developed to simulate the temporal and spatial distribution of anthropogenic and biogenic gaseous and particulate matter. In contrast, today's forecast of pollen concentration is often based on a few measurements in combination with the weather forecast using the specific knowledge of individual forecasters. Therefore, these forecasts are subjective and the spatial and temporal resolution is low. Within the last couple of years, new efforts have been undertaken to simulate the pollen dispersion applying the concepts which are commonly used in air pollution modelling.

The dispersion of pollen grains in the atmosphere depends on atmospheric flow and turbulence fields. Therefore, for the airborne trace species, one has to distinguish and take into account different scales. At the microscale, it might be justified to use the Gaussian type of models as developed by Walklate et al. (2004) for oilseed rape and by Jarosz et al. (2004) for maize. However, these kinds of models can only be applied close to the pollen source.

In our study, we will focus on the dispersion of allergenic pollen grains on the regional scale. Schüler and Schlünzen (2006) used a non-hydrostatic mesoscale model to simulate the dispersion of oak pollen in an area of up to $200 \times 200 \text{ km}^2$. The proposed parameterisation of the emission flux mainly depends on the estimated annual

H. Vogel (✉) · B. Vogel
Institut für Meteorologie und Klimaforschung,
Forschungszentrum Karlsruhe/Universität Karlsruhe,
Postfach 3640, 76021 Karlsruhe, Germany
e-mail: heike.vogel@imk.fzk.de

A. Pauling
Bundesamt für Meteorologie und Klimatologie MeteoSchweiz,
Zürich, Switzerland

pollen production and the vapour pressure deficit. They also took into account the pollen viability and parameterised it as a function of the amount of sunlight that the pollen gets during the transport. Due to a lack of observations they were not able to validate their model.

Sofiev et al. (2006) presented a feasibility study to use a model system that was originally designed for emergency modelling (Sofiev and Siljamo 2003; Siljamo et al. 2004). They used this model system to study the long-range transport of birch pollen to Finland. Their model includes parameterisations of the settling velocity and of the dry and the wet deposition. In order to prescribe the pollen emissions, they used a detailed birch forest map and climatological values for the pollen emissions. Comparisons with a limited number of observational data are presented showing the possibilities and the limitations of the modelled pollen distributions. The authors could demonstrate by their model results that pollen grains can be transported over quite large distances in the order of several hundreds of kilometres.

Pasken and Pietrowicz (2005) used a combination of the MM5 and the HYSPLIT_4 model to simulate oak pollen concentrations during a pollen episode that was observed at Clayton, Missouri, United States. They made rather rough assumptions for the emissions of the pollen grains and used the observations to tune the model. They prescribed emission fluxes that were constant in time and a pollen release that started at 1300 hours UTC and continued for 22 h. Although the model domain was rather large, only data from one observation station were available to compare with the modelled diurnal cycles of the pollen number densities. These comparisons show that there are still large discrepancies between observation and simulation.

A very crucial point in all kinds of dispersion modelling are the emission data. One problem arises from the fact that currently no detailed maps of the spatial distribution of the relevant plants are available. In the case of pollen grains the emissions are determined by several factors. Pollen emissions depend on the start and the intensity of the flowering season. For example, it is well known that the birch pollen flowering shows interannual variations (Clot 2001), and long-term trends (Menzel and Dose 2005).

The emission of pollen depends on meteorological variables such as wind stress, temperature and humidity (Rempe 1938; Puls 1987; Mullins and Emberlin 1997). Helbig et al. (2004) proposed a parameterisation that takes into account these individual factors. They applied this parameterisation to an isolated field in the Rhine Valley and could show that, especially in inhomogeneous terrain where secondary circulation systems are generating vertical velocities substantially greater than zero, pollen grains can travel larger distances. For that case no observational data were available.

In this study, we used a comprehensive model system to simulate a birch pollen episode that occurred in April 2006

in Switzerland. For that purpose we included the parameterisation for the pollen emission of Helbig et al. (2004) and generated a detailed map for the distribution of birch trees in Switzerland. We compared the modelled diurnal cycles of the pollen grain concentrations with measured data of six pollen counting stations in Switzerland, documenting the current abilities of an operational pollen forecast system. Finally, we discuss the necessary improvements and the requirements with respect to input data.

Materials and methods

Model description and necessary input data

The COSMO-Model (formerly LM; Doms and Schättler 2002) of the German Weather Service (DWD) is a non-hydrostatic mesoscale model and is part of the forecast system of the DWD. The standard model domain covers the whole of Europe. Due to its operational use, it is appropriate to use as the meteorological driver for a pollen forecast system. In order to calculate the temporal development of the pollen grain number density it is necessary to describe the emission flux, the transport by the mean wind, the diffusion by atmospheric turbulence, the coagulation, the sedimentation and deposition, the re-suspension, and the wash-out. Therefore, the COSMO model had to be extended by parameterisations which describe these processes to determine the temporal and spatial distribution of pollen grains from the local to the regional scale.

Based on the mesoscale model system KAMM/DRAIS/MADEsoot (Riemer et al. 2003) we developed the comprehensive model system COSMO-ART (ART = Aerosols and Reactive Trace Substances, <http://www-imk.fzk.de/tro/ACP/index.html>). This model system is used to simulate the spatial and temporal distribution of reactive gaseous and particulate matter and especially to quantify the feedback mechanisms between aerosol and climate processes on the regional scale. The model system is fully online coupled. It includes a treatment of the aging processes of soot particles. In addition to MADEsoot, detailed emission modules for mineral dust (Vogel et al. 2006), sea salt, and bacteria were added to the aerosol module. Identical numerical schemes and parameterisations are used for identical physical processes such as advection and turbulent diffusion. This avoids truncation errors and model inconsistencies. COSMO is verified operationally by DWD; the model system can be embedded by one-way nesting into individual global scale models such as the GME or ECMWF models. All components of the model system are coupled online with time steps of the order of tenths of seconds. Nesting of COSMO-ART within COSMO-ART is possible. Typical horizontal grid sizes

vary between 2.8 and 28 km. The model allows the simulation of the interaction of the aerosol particles with radiation and the feedback of this process with the atmospheric variables.

In order to include pollen as an additional component into the model system COSMO-ART the following simplifications are made. Coagulation is neglected. The equation that describes the transport, the turbulent diffusion, the sedimentation, and the washout of the total pollen number density is then given by:

$$\rho \frac{dq}{dt} = -\nabla \cdot \bar{F}_T - \frac{\partial}{\partial z} F_s - \lambda \cdot q + S \quad (1)$$

with

$$q = \frac{N_p}{N} \quad (2)$$

N_p is the number density of the pollen grains and N is the total number of particles per m^{-3} including the air molecules.

$$F_T = \overline{\rho \cdot v' \cdot q'} \quad (3)$$

is the turbulent pollen flux that is parameterised according to temperature and specific humidity. ρ is the air density, v' and q' are the turbulent fluctuations of the wind speed and the mass density of the pollen grains.

The sedimentation flux F_s is given by:

$$F_s = \rho \cdot q \cdot v_s \quad (4)$$

The settling velocity v_s is calculated by:

$$v_s = \sqrt{\frac{4 \cdot \rho_p \cdot d_p \cdot g}{3 \cdot \rho \cdot c_d}} \quad (5)$$

d_p is the diameter of the pollen grains. ρ_p is the pollen grain density that depends on the water content (Aylor 2002). c_d is the drag coefficient parameterised according to an approach of Fuchs (1964) and Friedlander (1977) and g is the acceleration of gravity. λ is the washout coefficient that is determined in the following way:

$$\lambda(d_p) = \frac{3 \cdot E(d_p, D_r) \cdot P}{2 \cdot D_r} \quad (6)$$

E is the collision efficiency after Slinn (1983), D_r is the diameter of the rain droplets, P is the precipitation rate in $m s^{-1}$.

The source term in equation (1) is then given by the divergence of the vertical mass flux F_e , calculated on the numerical grid.

$$S = -\frac{1}{N} \cdot \frac{\partial F_e}{\partial z} \approx \frac{1}{N} \cdot \frac{F_e}{\Delta z_s} \quad i = 1, 3 \quad (7)$$

To take this into account, the parameterisation of Helbig et al. (2004) was chosen and will be briefly described in the following.

The basic idea of our parameterisation is that the vertical flux of pollen grains F_e at the top of the vegetation is proportional to the product of a characteristic concentration and a characteristic velocity:

$$F_e = w_f \cdot c_e \cdot K_e \cdot \frac{q_p}{LAI \cdot h} \cdot u_* \quad (8)$$

The friction velocity u_* is used as the characteristic velocity. The pollen production q_p is given in pollen grains per square metre. It describes the number of pollen grains produced during one season. It therefore reflects the maximum number of pollen grains which can be emitted. Of course, q_p is reduced by the already emitted amount of pollen grains. LAI denotes the leaf area index and h the typical canopy height of the corresponding plant species. c_e is considered a plant-specific factor that describes the likelihood to bloom. This factor takes into account that not all flowers are blooming at the same time, although the meteorological conditions are ideal for pollen release. Instead, the number of flowers increases with time until a maximum is reached. Afterwards, the number decreases again until the end of the pollen season. W_f is a weighting factor that will be explained below.

It is obvious that the available pollen grains cannot be emitted into the atmosphere if the meteorological conditions are unfavourable. K_e is a correction factor that takes into account some previous findings that documented the dependency of the pollen emissions on threshold values of temperature T_{te} , humidity U_{te} , and wind speed $|\vec{v}|_{te}$ (for details see Helbig et al. 2004). Threshold values for temperature were found for different plant species by Wachter (1982), Fritz and Gressel (1983) and Puls (1987). In contrast to this, threshold values for U_{te} , and $|\vec{v}|_{te}$ could not be found. They had to be assumed for this study. c_1 , c_2 , and c_3 are plant-specific constants to weight the influence of the corresponding meteorological resistance and will be set equal to 1 in this study.

Model domain and input data

We simulated a pollen episode which occurred from 19 to 22 April 2006 in Switzerland. The model domain covers the central part of Europe. The horizontal grid size is 7 km in each direction. 40 layers are used in the vertical direction and the top of the model domain is at 24 km. The time steps are in the order of tenths of seconds. The model system COSMO-ART is driven by the initial and the boundary conditions which are taken from the ECMWF model IFS. The boundary conditions are updated every 6 h. In the following, however, we will only present the results for a sub-domain for which we had detailed information about the occurrence of birch trees. Figure 1 shows the topography of the sub-domain which covers the whole of Switzerland. It also

shows the surface wind fields at 1200 hours UTC for four consecutive days. Only every third wind vector is shown.

Distribution of birch stands

Applying the parameterisation of pollen emissions requires a dataset describing the spatial distribution and the density of birch trees. These input data are crucial for the modelling of pollen dispersion. In Switzerland, land use data which give specific information on birch trees are available for forested areas. The National Forest Inventory (Schweizerisches Landesforstinventar; WSL 2006) provides gridded information on the percentage of birch trees on a 1-km resolution. This dataset was produced using a systematic sample of 500 m² at every grid point. For the non-forested areas we relied on land use data by the Bundesamt für Statistik (source: Arealstatistik 1992/97, BFS GEOSTAT). However, this dataset contains no direct birch information. It uses a classification scheme of 74 land use categories and is resolved on a 0.1-km grid.

These two datasets were combined and integrated on the 7-km resolution of COSMO-ART using the following procedure. For each forested grid box of the COSMO-ART, all birch percentages from the National Forest Inventory were added up. Then, the birch density categories of low, medium, and high were assigned to the terciles of the added birch percentages. For the non-forested COSMO-ART grid boxes, we assigned to each category of the land use dataset the birch densities 0 (none), 1 (low), 2 (medium), and 3 (high) and added them up for each COSMO-ART grid box. The lowest 20% were considered as virtually birch-free and the remaining 80% of the data was assigned the birch categories low, medium and high according to the terciles, and were then combined with the birch density data derived from the National Forest Inventory to produce the final birch distribution dataset encompassing the whole of Switzerland (Fig. 2).

Since we had detailed data on birch stands and land use only for Switzerland, we will focus on the results in the area which is shown in Fig. 2. The stations depicted in Fig. 2 are

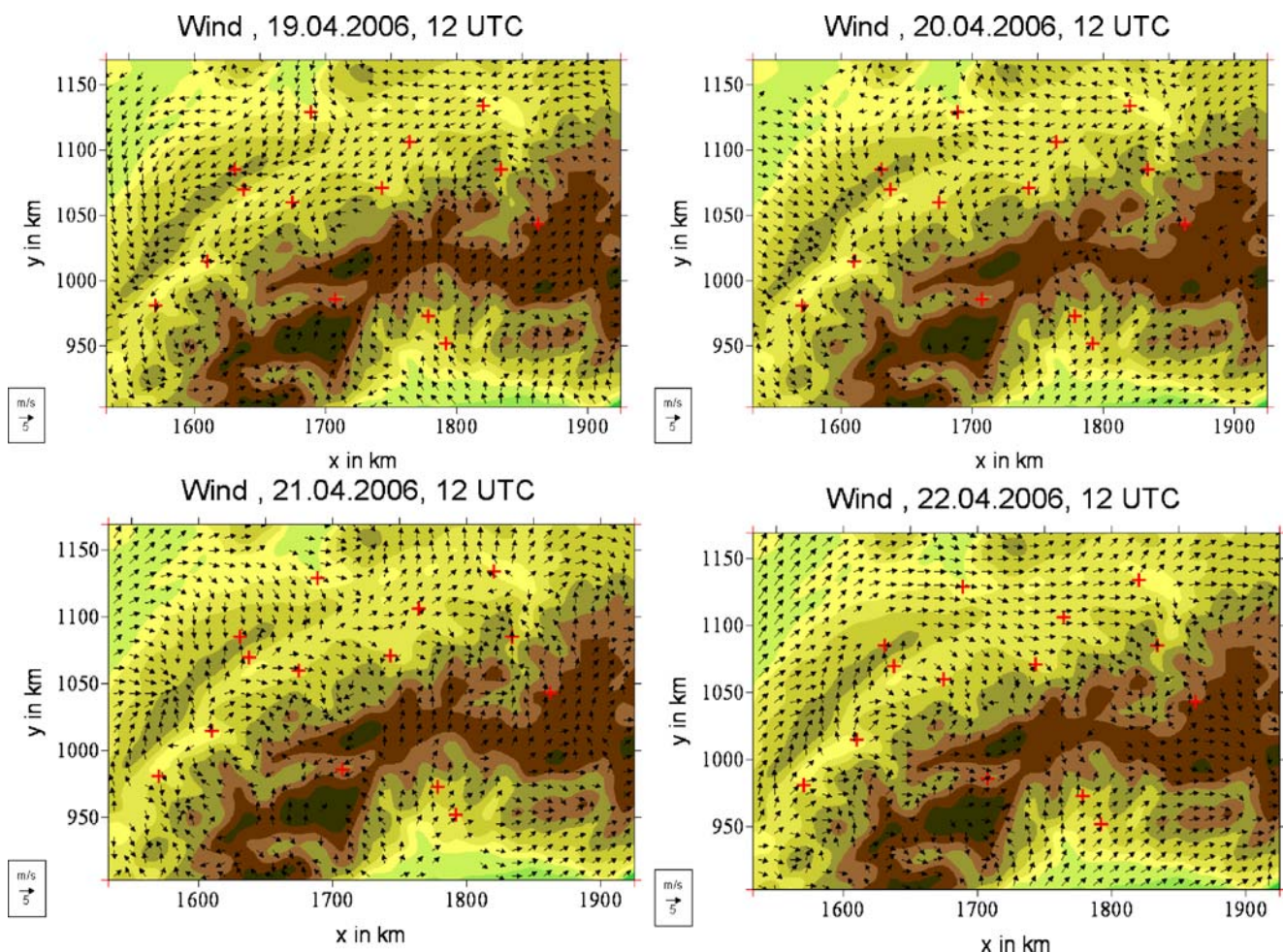


Fig. 1 Simulated surface wind field at 1200 hours UTC on four consecutive days. The red crosses denote the pollen measurement sites. The colour-shaded areas give the terrain height. The lower left corner is at 45°17'54"N, 5°23'39"E

those where detailed pollen counts with a time resolution of 2 h were carried out. In addition, the locations of those stations are marked where daily averaged pollen concentrations are available. All stations belong to the national pollen monitoring network (Nationales Pollenmessnetz NAPOL).

The pollen grains were collected by Burkhard samplers. The samplers are situated on the roof of buildings 10–40 m above ground. Birch stands are located in the vicinity of many samplers. The Burkhard sampler allows a time resolution of 2 h which makes it possible to compare modelled diurnal cycles and observations.

Results

The simulation was started on at 0000 hours UTC on 19 April 2006. We chose this date as it is during the birch pollen season

and because it was a period of fair weather with almost no precipitation. The simulation was continued for 92 h which might be the upper limit as long as no data assimilation or nudging in the inner domain is carried out inbetween.

As the wind speed is an important factor that determines the emissions of the pollen grains, we will first compare the simulated and the observed wind speeds at those stations where we had the pollen counts with the high temporal resolution.

Figure 3 gives the temporal development of the observed and the simulated surface wind speeds. It shows that the wind speed is quite well simulated at most stations with the exception of Visp. The observed wind speed at Visp is much higher than the simulated one during the day. During night-time the wind speed is often overestimated by the model system. Visp is located in the Rhone valley whose topography is relatively well reproduced by the model. However, wind speed and direction are also influenced by narrow side valleys such as the valley of Zermatt. They are

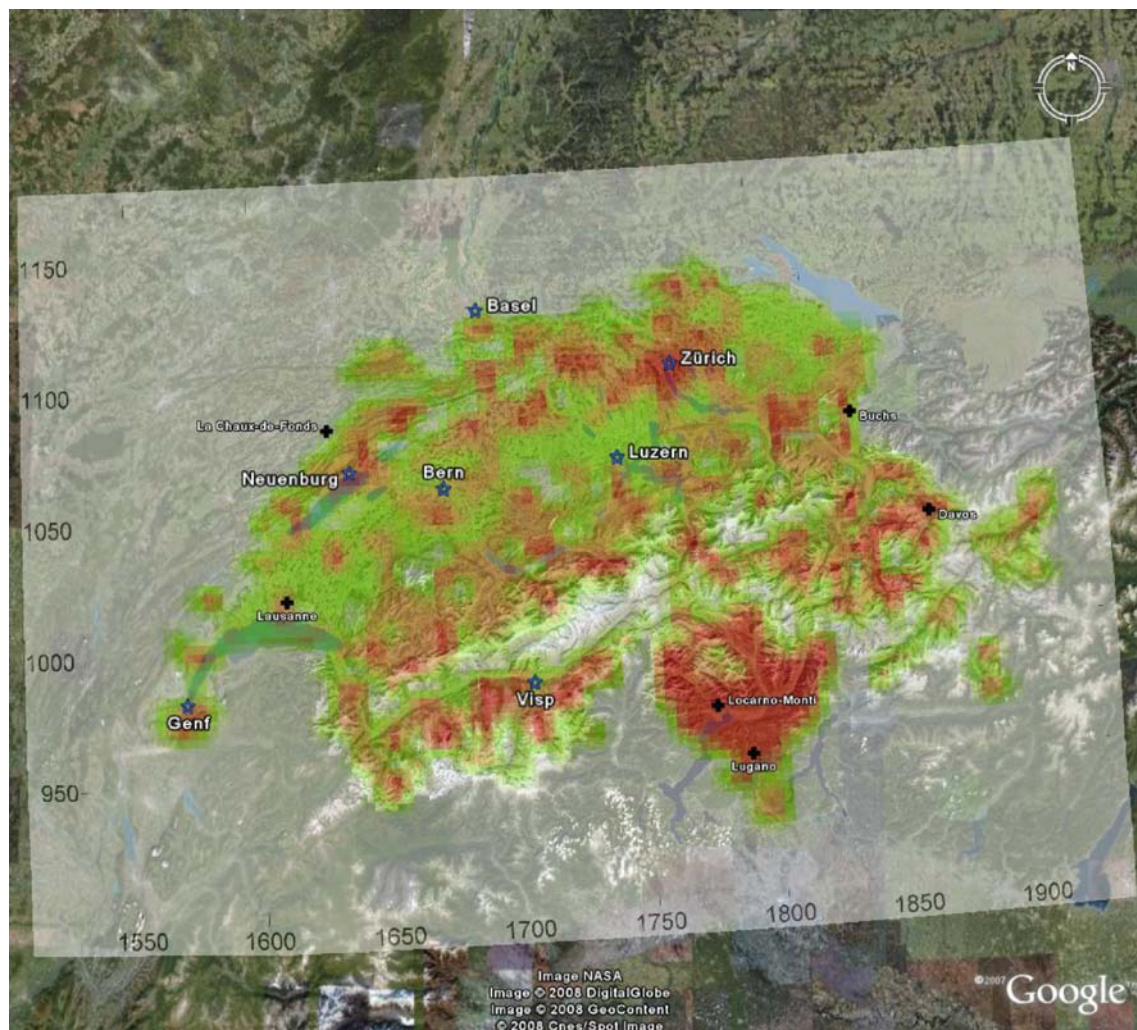


Fig. 2 Spatial distribution of the population density classes (green low, orange medium, red dense) of the birch trees and location of the pollen count stations. Stars indicate those pollen count stations with

2-h resolution whereas black crosses stand for stations where only daily averages of the pollen concentration were available

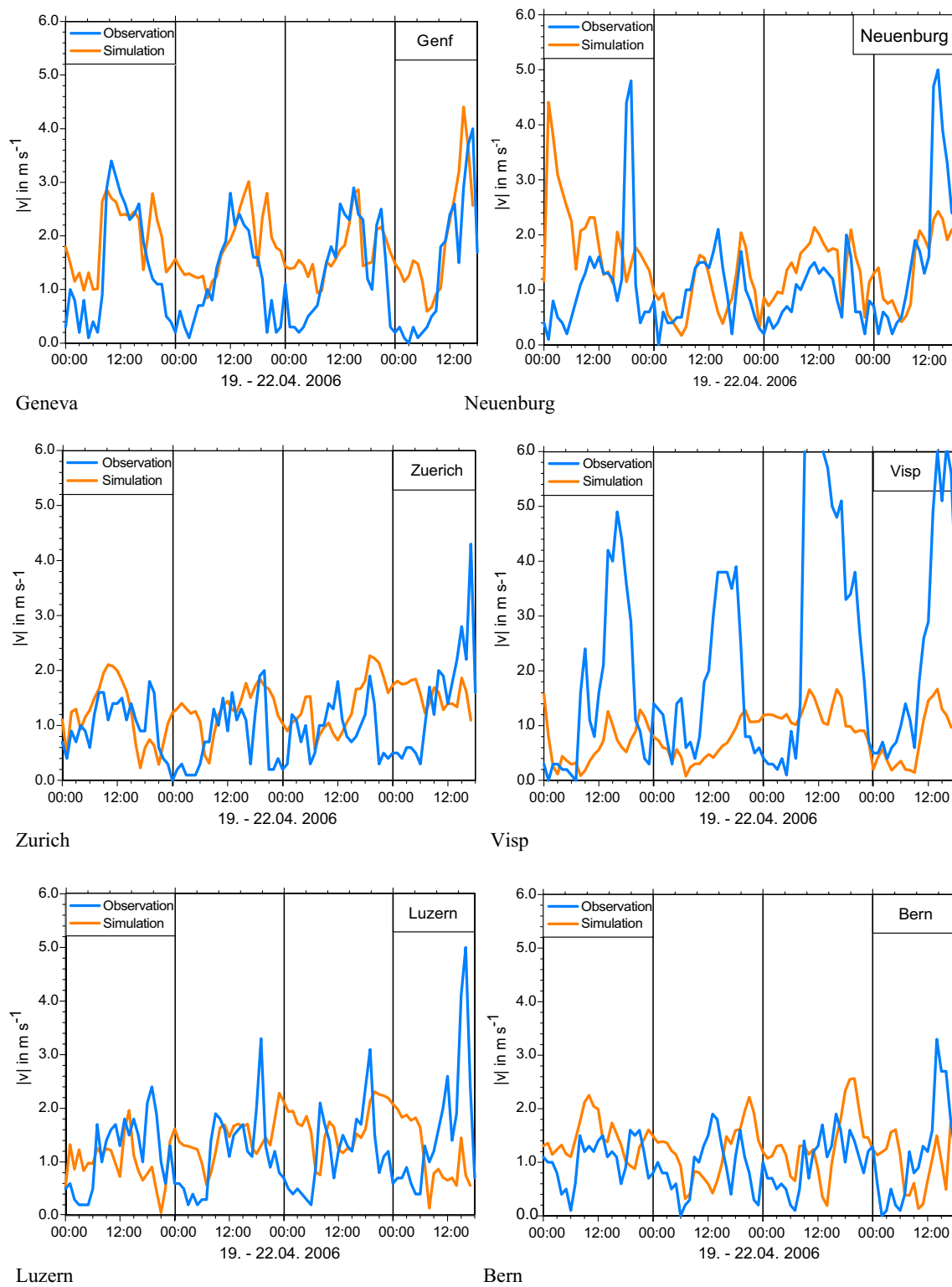


Fig. 3 Simulated and observed diurnal cycles of the wind speed at 10 m above surface

smaller than the used grid size of 7 km and are causing effects such as small-scale wind systems and channelling (which may explain the underestimation of the wind speed during the day). These phenomena need a higher resolution to be modelled (Fig. 3).

Although we have a quite detailed map of the spatial distribution of birch trees, it is still more a qualitative than a quantitative distribution. In addition, we have no pollen emissions outside Switzerland. For that reason, we have chosen the following procedure. We carried out three individual model runs where in each run only emissions of a single birch density class was allowed and the weighting function w_f in equation 8 was set equal to one. By this procedure, we end up with three time dependent three-dimensional concentration distributions of birch pollen. We then assumed that the daily averaged pollen concentration at each station is a linear combination of results of the individual model runs. Finally, we applied a linear regression to minimise the deviation between the observed and the simulated daily averages. The equation for this fit is given by

$$\sum_{l=1}^L (m_l - A \cdot \bar{N}_{p,1,l} - B \cdot \bar{N}_{p,2,l} - C \cdot \bar{N}_{p,3,l} - D)^2 = \text{Min} \quad (9)$$

Solving this equation results in $A = 0.2$, $B = 0.65$, $C = 3$, and $D = 87$.

Figure 4 shows the comparison of simulated and observed daily averages of the pollen concentration after regression was applied. The figure shows that the ratio of

modelled and measured pollen concentrations is in most cases in the interval between 0.5 and 2. The positive value of D is consistent with the fact that no emissions were allowed outside Switzerland.

The parameters A – D are used to calculate the diurnal cycles of the pollen number density for those stations where we had the 2-hourly pollen counts (Bern, Genf/Geneva, Luzern, Neuenburg, Visp, and Zürich).

$$N_p(x, y, z, t) = A \cdot N_{p,1}(x, y, z, t) + B \cdot N_{p,2}(x, y, z, t) + C \cdot N_{p,3}(x, y, z, t) + D \quad (10)$$

$N_{p,1}$, $N_{p,2}$, and $N_{p,3}$ are the concentrations which were calculated using emissions from a single birch density class and $w_f = 1$.

The comparison of the observed and simulated diurnal cycles of the pollen density is presented in Fig. 5 for the individual stations. The highest deviations between observed and simulated concentration occur for the station Visp, where the observed concentrations are much higher than the simulated ones. To some extent this could be expected since the observed wind speeds at this station are much higher (Fig. 3) and therefore the emissions and the real concentration should be larger than the simulated ones. Additionally, the transport and the sampling efficiency of the trap is more effective at high wind speeds.

The best agreement is found for the stations Luzern and Zürich (Fig. 5). At both stations, the increase on 20 April and the peaks on 21 April is featured by both the measurements and the simulations. Luzern is located in

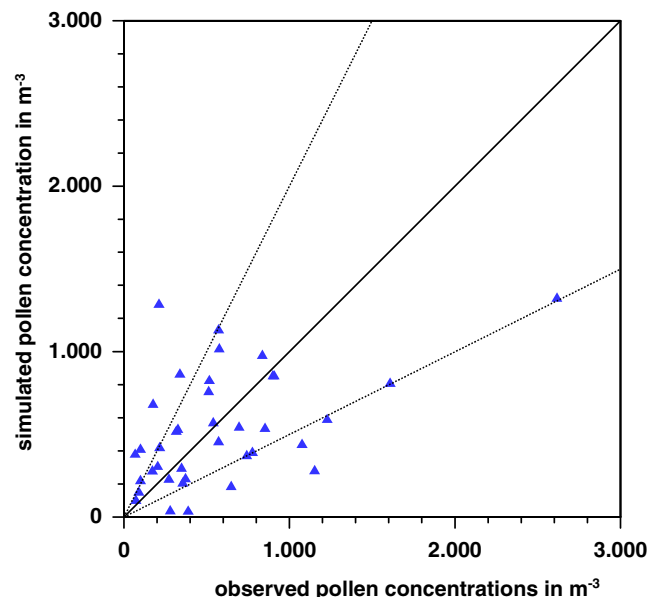


Fig. 4 Simulated versus observed daily averaged number densities of birch pollen grains. Each data point represents one daily averaged value of each of the pollen count stations shown in Fig. 2

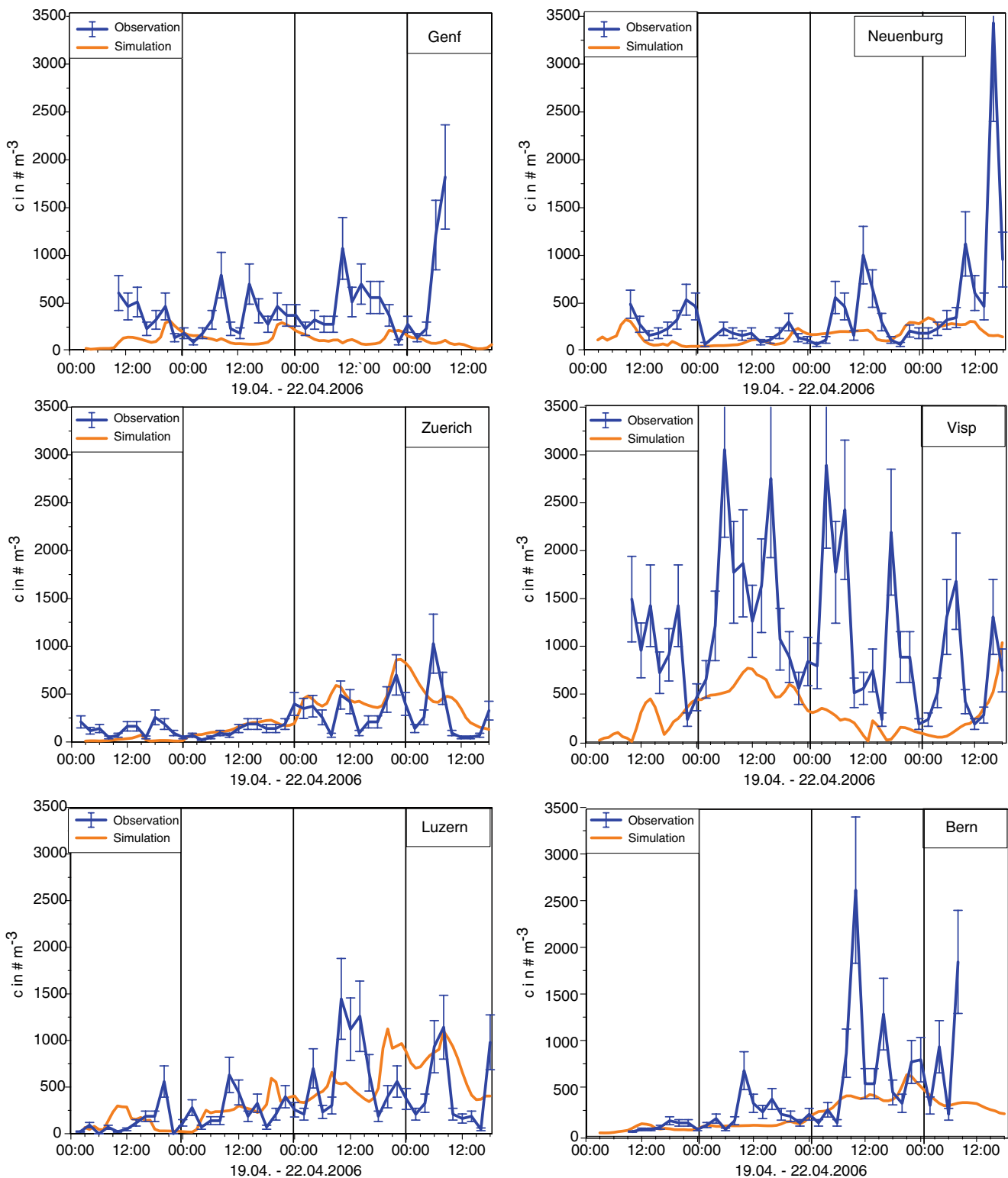


Fig. 5 Simulated and observed diurnal variations of the number density of the pollen grains

the more inner part of the area where emissions are allowed and Zürich is located in an area where the density of the birch stands is high, therefore the impact of the zero concentrations that are advected from those areas where no

emissions are allowed is supposed to be small. It is obvious that single spikes as they are observed at individual stations and time periods are not reproduced by the model and might be caused by local effects in the vicinity of the pollen stations.

At the station of Geneva, the maximum tends to occur around midday. Interestingly, there is also a daily maximum in the simulation but it is delayed by 6–12 h compared to the measurements and is less well pronounced. In Geneva, the pollen trap is situated within the city atop a building 42 m above ground while the other pollen traps are typically located at only 15–20 m above ground. It is argued that, in the case of Geneva, the model underestimates turbulence during the day so that it takes longer to reach the pollen trap. Turbulence depends on the roughness and the availability of heating surfaces. Both factors are increased in towns, helping to explain the delayed peaks in the simulation.

Generally, the peak values in the measurements cannot be found in the simulations. This is not surprising as the measurements are subject to random processes that introduce errors. They include various sampling errors such as the limited volume of the air sampled, counting of only parts of the sample and sampling efficiency of the trap. Comtois (1998) gives an overview of possible errors in aerobiological data. According to Comtois et al. (1999), the errors in pollen counts range from 10 to over 30% depending on pollen abundance and sample size. Additionally, pollen counts may also be influenced by local effects in the vicinity of the pollen stations that are below model resolution. Hence, it is not possible to model the peak values. On the other hand, the level of daily concentrations is well modelled (Fig. 5). Since this is the focus of pollen forecasts, the simulations represent a promising start for their future use in operational pollen forecast systems.

Discussion and conclusions

We have included a parameterisation of the pollen emission flux into the comprehensive model system COSMO-ART. In order to calculate the birch pollen emissions, it is necessary to have detailed data about the spatial distribution of the birch trees. We derived such data for the area of Switzerland. This leads to a discrimination of sparse, dense and very dense birch tree populations. Based on this rather qualitative information, we carried out individual model runs for each density class and applied a simple procedure that combines simulated and observed daily averages of the pollen concentrations to derive a more quantitative discrimination based on the individual tree densities. Based on this weighting function, we simulated the diurnal variation of the pollen concentration for 4 consecutive days (19–22 April 2006).

For the station Visp, we found a distinct underestimation of the pollen concentrations by the model for most of the time that is probably linked to an underestimation of the wind speed. For those stations which are located in areas with dense birch tree populations, the agreement between model results was quite satisfactory.

Nevertheless, there are still several unsolved problems. We need information such as detailed vegetation maps, the spatial distribution of the beginning of flowering, and a specification of the necessary parameters for the emission module based on sophisticated field campaigns. In the event that these are solved, a numerical model that uses state of the art methods to treat the transport and the diffusion of particles in the atmosphere is a promising tool for an operational pollen forecast. The advantage of COSMO-ART is that it also treats other natural and anthropogenic particles and gas phase substances that are suspected of enhancing the allergenic potential of pollen grains or fragments. Therefore, these interactions can also be treated by the model system.

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