



Numerical modelling of pollen dispersion on the regional scale

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Abstract

New parameterisations were developed to calculate the emission and resuspension flux of pollen grains. These new parameterisations were included in the comprehensive mesoscale model system KAMM/DRAIS. Two types of simulations were performed. In the first case, horizontally homogeneous meteorology was assumed. In this case, pollen concentration rapidly decreased with the distance from the source. In the second case, where the fully three-dimensional model was applied, atmospheric lifetime of the pollen grains increased remarkably. This was mainly caused by the vertical wind speeds induced by topographic effects. Consequently, the pollen grains could travel much larger distances until they were deposited and finally removed from the atmosphere. This is an important finding with respect to the problem of cross pollination. Due to the lack of measurements, a number of parameters had to be assumed. However, the parameterisation proposed may well serve as a starting point of a daily pollen forecast with numerical models.

1. Introduction

Interest in pollen dispersion and pollen forecasting is growing mainly for two reasons. Firstly, there is the health aspect; allergies are caused by the allergens in the pollen grains. An increasing number of patients in industrialised countries are reported.¹ As an example, the actual number of patients in Germany is of the order of 12 million. Compared to the 2 million allergy patients in 1977 (Kersten and Puls, 1984), the number has increased by a factor of 6. Local pollen concentration varies extremely in time and space. To minimise the symptoms, allergy patients therefore have to know when and where there will be high pollen concentrations (Allergie-, Dokumentations- und Informationszentrum (ADIZ)).² To issue early warnings for the patients in Germany, the “Stiftung Deutscher Polleninformationsdienst” (German pollen information service foundation) was founded in 1983. Until the beginning of 2000, already 60 pollen traps had been set up for yearly pollen counting all over Germany. Regional

pollen forecast presently is based on pollen counting, phenological data, and the weather forecast by the “Deutscher Wetterdienst” (German weather service).

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. It is obvious that the understanding of pollen dispersion will gain importance in the future (McCartney and Lacey, 1991; Hunt et al., 2001).

Pollen grains are of irregular shape (Gregory, 1973) and diameter (Pohl, 1937b; Stanley and Linkens, 1974; Pickhardt and Fluri, 2000). They can hydrate and dehydrate (Pohl, 1937b; Aylor, 2002). They may build up aggregates if they are entomophilous pollen grains, due to a pollen kit on their surface (Pohl, 1937a; Heß, 1990). They have different densities and settling velocities (Pohl, 1937b; Gregory, 1973; Di-Giovanni, 1995; Jackson and Lyford, 1999).

Pollen grains have limited and mostly unknown viabilities, depending on the species (Stanley and Linkens, 1974; Edmonds, 1979; Treu and Emberlin, 2000). The concentration thresholds that cause symptoms for the patients also depend on the species (Puls, 1982; Kersten and Puls, 1984; von Wahl et al., 1989).

Present pollen modelling can be divided into two groups. The first group deals with forecasting the start, end, and duration of pollen seasons. Here, mainly a single meteorological variable is summed (Peeters, 2000; Clot, 2001; Laadi, 2001) until predetermined thresholds are reached or regression equations are applied. Regression equations consist of correlation parameters either between meteorological variables and pollen concentrations (Moreno-Grau et al., 2000; Latalowa et al., 2002) or among meteorological variables averaged over a certain time sequence (Emberlin et al., 1999; Laaidi, 2001; Groom-Adams et al., 2002).

The second group deals with the numerical simulation of the temporal and spatial distributions of pollen grains. Spatial pollen dispersion was first implemented in a numerical model by McCartney and Lacey (1991) for oilseed rape. With concentration measurements within and above the field and meteorological data, they found a multiple regression equation describing average pollen concentrations. Hunt et al. (2001) compared these results with those of their three-dimensional model. This Gaussian plume model ADMS (Carruthers et al., 1994) includes dry deposition and a source flux described as the product of pollen concentration and friction velocity.

Kawashima and Takahashi (1999) developed a dispersion model for the Japanese cedar. Based on measured concentrations and meteorological data, they found high correlations between air temperature and wind speed deviations with airborne pollen concentrations. The corresponding multiple regression equation provides the number of cedar pollen grains emitted per time. Multiplication by the percentage area of cedar forest gives the source term which was incorporated in a one-layer Eulerian type diffusion model. In addition, they integrated a flowering time map for the Japanese cedar in their model domain. Considering these results together with a map developed for the strength of chest nut pollen sources (Puppi et al., 1992), Hidalgo et al. (2002) predicted the olive pollen grain concentration in the province of Cordoba. Their model system consists of three modules, one for emission, one for meteorology, and one for dispersion. The emission module comprises a pollen production map calculated with the percentage area

of olive trees in the square, the determined pollen production per tree, and the influence of the meteorological conditions. By applying neural networks to the concentrations measured, a temporal dispersion of the pollen production in the model region was obtained.

Pietrowicz and Pasken (2002) linked the meteorological model MM5 (Dudhia et al., 2001) with the dispersion model HYSPLIT_4 (Draxler and Hess, 1998) for predicting pollen concentrations of oak pollen grains. The dispersion model accounted for dry and wet deposition as well as for resuspension. Source strength of the tree species was determined from the oak tree density per km² and the pollen emission over a diurnal (caused biologically) and seasonal cycle (caused by the meteorological conditions of the last season).

Other less complex dispersion models were developed. For a single site Norris-Hill (1995) developed a model for grass pollen grains based on regression analysis between measured concentrations and meteorological variables. More detailed, but again for one site only, Spitzer (1997) presented a mathematical model for the prediction of local daily averaged concentrations of mugwort pollen grains. Basically, it consists of a production and a transport term, leading to an equation that can be solved by recursion.

In this study new parameterisations were developed to calculate the emission and resuspension of pollen grains. These new parameterisations were implemented in the comprehensive mesoscale model system KAMM/DRAIS (Vogel et al., 1995) to determine the temporal and spatial distribution of pollen grains from the local to the regional scale. First applications of the extended model system to hazel and alder pollen will be shown, and the remaining uncertainties and open questions will be discussed.

2. The treatment of pollen dispersion

To calculate the temporal development of the pollen grain number density, it is necessary to describe the emission flux, transport by the mean wind, diffusion by atmospheric turbulence, coagulation, sedimentation and deposition, resuspension, and wash-out. Since KAMM/DRAIS already includes the treatment of aerosol particles (MADEsoot, Riemer et al., 2003), the model system had to be extended by new parameterisations for the emission flux and resuspension of pollen grains. Parameterisation of the settling velocity which is necessary to determine the sedimentation

flux is based on recent findings by Aylor (2002). Furthermore, deposition of pollen grains is assumed to be negligible compared to their sedimentation. Wash-out processes are not taken into account. Coagulation is neglected as well, since the typical atmospheric number densities of the pollen grains are quite low.

2.1. Parameterisation of the emission flux

As in this study the parameterisations were to be kept as general as possible, the maximum occurring pollen grains in one season from one plant species, the so-called pollen production, was chosen to be the starting point. Pohl (1937a) already tried to find out the pollen production of different plants and trees. For a few plant species he reported the pollen production per square meter land. Molina (1996) determined the number of pollen grains for 10 different plant species. However, pollen grain numbers were given per branches, trees, and crown diameter. Pollen production is supposed to depend on different factors, such as the climate of the preceding year (Stanley and Linkens, 1974; Faegri and Iversen, 1989), the weather of summer and autumn (Leuschner, 1971) and alternatively of spring (Solomon, 1973), vernalisation (Puls, 1987) or simply on biological rhythms (Stanley and Linkens, 1974; Puls, 1987). These dependencies were not taken into account in this study.

Several authors documented that the emission of pollen grains strongly depends on meteorological conditions (Rempe, 1938; Puls, 1987; Mullins and Emberlin, 1997). This results in a diurnal cycle of emission according to a kind of biological cycle. The latter often is misleadingly taken to explain the emission of pollen grains. Different plant species require different meteorological conditions to open their flowers. Concerning anemophilous trees which flower in early spring, high temperature, low humidity, and moderate wind speed favour a passive dehydration which then leads to a bursting of the anthers (Stix and Grosse-Brauckmann, 1970; Fuckerieder, 1976; Kersten and Puls, 1984; Puls, 1985; Puls, 1987). In contrast to this, grasses require a low temperature and high humidity, because now it is a more hygroscopic process that leads to the bursting of the anthers (Fuckerieder, 1976; Puls, 1985; Puls, 1987). It is therefore obvious that individual meteorological thresholds are necessary to define the onset of the emission of pollen grains.

The basic idea of our parameterisation is that the vertical emission 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:

$$F_e = c_e \cdot K_e \cdot c^* \cdot u_* \quad (1)$$

Friction velocity u is used as the characteristic velocity. The characteristic concentration c^* is calculated as:

$$c^* = \frac{q_p}{I_c} \quad (2)$$

q_p is given in pollen grains per square meter, describing the number of pollen grains produced in 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. I_c is a characteristic length given by:

$$I_c = LAI \cdot h_c \quad (3)$$

with LAI denoting the leaf area index and h_c 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. To take this into account, the following parameterisation was chosen:

$$c_e = 4 \cdot c_b \cdot \left(\frac{d}{S} - \frac{d^2}{S^2} \right) \quad (4)$$

d is the actual day of the pollen season lasting for the time interval S . Outside the pollen season, c_e is set to zero. Assuming that K_e and u_* are constant in the course of the day, c_b can be estimated roughly. In this case, the following relation was found:

$$c_b \sim \frac{3 \cdot I_c}{2 \cdot S \cdot K_e \cdot u_*}$$

Using this relation and a pollen season S of 30 days, c_b can be approximated by $1 \cdot 10^{-4}$.

It is obvious that the available pollen grains cannot be emitted into the atmosphere, if the meteorological conditions are unfavourable. This behaviour is taken into account by the meteorological adjustment factor K_e . To parameterise K_e , the methods for dust transport (Owen, 1964; Shao and Leslie, 1997; Lu and Shao, 2001) were employed to a certain extent.

For activating the saltation process leading to dust entrainment, a certain friction velocity, the so-called threshold friction velocity u_{*t} , is introduced. Shao and Lu (2000) developed a physical parameterisation for u_{*t} for dry and bare soils by:

$$u_{*t} = \left(a_1 \left[\frac{\rho_p}{\rho} \cdot g \cdot d_p + \frac{a_2}{\rho \cdot d_p} \right] \right)^{1/2}. \quad (5)$$

The factors $a_1 = 0.0123$ and $a_2 = 3 \cdot 10^{-4} \text{ kg s}^{-1}$ were defined on the basis of the results obtained from a wind tunnel experiment by Greely and Iversen (1985). ρ_p is the particle density, ρ air density, and g gravity acceleration.

Since the pollen grains are not simply lying on the soil, but located in the flowers which require certain meteorological conditions to open, a modified threshold friction velocity u_{*te} was introduced:

$$u_{*te} = u_{*t} \cdot \alpha. \quad (6)$$

The meteorological coefficient α can be understood as a kind of resistance against the pollen release by the meteorological conditions. It is composed of three meteorological resistances controlling pollen release:

$$\alpha = \frac{3}{\alpha_T + \alpha_U + \alpha_v}. \quad (7)$$

In detail, α_T is the resistance due to temperature, α_U is due to relative humidity, and α_v to wind speed. The following parameterisations were developed for these resistances:

$$\begin{aligned} \alpha_T &= c_1 \cdot \frac{T}{T_{te}} \\ \alpha_U &= c_2 \cdot \frac{U_{te}}{U} \\ \alpha_v &= c_3 \cdot \frac{|\vec{v}|}{|\vec{v}|_{te}} \end{aligned} \quad (8)$$

T_{te} , U_{te} , and $|\vec{v}|_{te}$ are thresholds for temperature, humidity, and wind speed. Threshold values for temperature were found for different plant species by Wachter (1982), Fritz and Gressel (1983), and Puls (1985). 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. The way α_U is defined (equation (8)) is valid for most deciduous trees. For grasses the reciprocal ratio should be considered, as they require a certain wetness for anther bursting. c_1 , c_2 , and c_3 are plant-specific constants to weigh the influence of the

corresponding meteorological resistance. Finally, K_e is determined as follows:

$$\begin{aligned} K_e &= \left(1 - \frac{U_{*te}}{u_*} \right) & u_* > u_{*te} \\ K_e &= 0 & u_* \leq u_{*te} \end{aligned} \quad (9)$$

2.2. The settling velocity

Aylor (2002) studied settling velocities of pollen grains both from the experimental and from the theoretical point of view. Based on a series of measurements for corn (*Zea mays*) pollen grains, he derived an equation for the settling velocity. It takes into account the variability of the density of the pollen grains due to their ability to hydrate and dehydrate. His results were also used for this study. Settling velocity v_s is calculated by:

$$v_s^2 = \frac{4 \cdot \rho_p \cdot d_e \cdot g}{3 \cdot \rho \cdot c_d}. \quad (10)$$

In the formulation found by Fuchs (1964) and Friedlander (1977) for the settling velocity, Aylor (2002) replaced the particle diameter d_p by the volume-equivalent diameter d_e and the constant particle density ρ_p by a pollen grain density that depends on the water content. Applied to a prolate spheroid with the major and minor principal radius a and b , d_e can be expressed as:

$$d_e = 2 \cdot \sqrt[3]{a^2 \cdot b} \quad (11)$$

c_d is the drag coefficient parameterised according to an approach of Fuchs (1964) and Friedlander (1977):

$$c_d = \frac{24}{Re_p} \cdot (1 + 0.158 \cdot Re_p^{2/3}) \quad (12)$$

Re_p is the particle Reynolds number. ρ_p describes the dependence of the water content of the pollen grain. In accordance with Aylor (2002), it is given by:

$$\rho_p = \rho_{H_2O} \cdot \left(1 - \left(\frac{d_d}{d_e} \right)^3 \right) + \rho_{solid} \cdot \left(\frac{d_d}{d_e} \right)^3 \quad (13)$$

d_d is the diameter of the dry pollen grain, ρ_{solid} the density of the solid material of the pollen grain, and ρ_{H_2O} the density of water.

Although d_e in reality depends on the water content of the pollen grain, a constant value was used.

2.3. Parameterisation of the resuspension

Aylor (1976) studied the resuspension of ragweed pollen grains and reasoned that strong wind gusts or local accelerations of the flow, e.g. initiated by the leaf geometry, are required for resuspension.

We made the assumption that the pollen grains can only be resuspended at those places, where sedimentation actually takes place. This assumption was made, since little is known about the viability of pollen grains after they get in contact with surfaces. The sedimentation flux F_e at the lower boundary on the surface is given by:

$$F_s = c \cdot v_s \quad (14)$$

where c is the number density of the pollen grains close to the surface.

The vertical resuspension flux F_r is parameterised as follows:

$$F_r = c_r \cdot K_r \cdot F_s \quad (15)$$

c_r is a pollen-specific and plant-specific parameter. This parameter could take into account the buoyancy forces as those caused by air bags. Here, a constant value is chosen for c_r , as given in Table 2. Similar to the emission flux of the pollen grains, K_r characterises the meteorological limitations for resuspension. In order to parameterise K_r , a new threshold friction velocity u_{*tr} is defined:

$$u_{*tr} = u_{*l} \cdot \beta \cdot c_s \quad (16)$$

$$\beta = \frac{2}{\beta_U + \beta_v}. \quad (17)$$

It is assumed that the meteorological coefficient β for the resuspension depends on the relative humidity and the wind speed only.

In contrast to this, resuspension is promoted by wind gusts. They are supposed to be the main cause of resuspension. Air temperature was considered not to influence the resuspension process. Hence, the meteorological coefficient β consists of two resistances only. They are calculated in the same way, but with different threshold values U_{tr} and $|\vec{v}|_{tr}$:

$$\begin{aligned} \beta_U &= c_4 \cdot \frac{U_{tr}}{U} \\ \beta_v &= c_5 \cdot \frac{|\vec{v}|}{|\vec{v}|_{tr}}. \end{aligned} \quad (18)$$

The surface-depending constant c_s is calculated as:

$$c_s = 2 \cdot \frac{z_0}{z_{0r}} \quad (19)$$

z_{0r} which is used for normalisation equals 1 m. To control the influence of the corresponding meteorological resistance, the plant-specific constants c_4 and c_5 must differ from those of emission, still they have the same task.

Finally, K_r is given by the following equation:

$$\begin{aligned} K_r &= \left(1 - \frac{u_{*tr}}{u_*}\right) & u_* > u_{*tr} \\ K_r &= 0 & u_* \leq u_{*tr} \end{aligned} \quad (20)$$

3. Simulated pollen grain distributions

The new parameterisations described in the previous section were implemented in the KAMM/DRAIS model system. Meteorology is described by the non-hydrostatic mesoscale model KAMM (Adrian and Fiedler, 1991). This part is coupled with a surface vegetation model to determine the lower boundary conditions for temperature and humidity (Schädler, 1989; Lenz, 1996). The model part DRAIS is used to calculate turbulent transport (Tangermann-Dlugi and Fiedler, 1983), chemical reactions, and physical and chemical behaviour also of aerosols (Riemer et al., 2003). The model system has already been validated by comparison with observations in several applications (Vogel et al., 1995; Nester et al., 1995; Vogel et al., 1999; Hammer et al., 2002; Riemer et al., 2003). Recently, the model was applied to investigate the influence of aerosols on the chemical and radiation conditions of the atmosphere (Riemer, 2002) as well as the impact of car-induced turbulences on the dispersion of coarse particles in the vicinity of a highway (Bäumer, 2003). The whole model system is run in a coupled mode.

Here, model simulations were carried out with the extended model system in order to simulate the temporal and spatial distribution of pollen grains. With these model simulations the following questions were addressed:

1. Which distances from the source area can the pollen grains reach depending on the meteorological situation?
2. How large are the spatial and temporal variabilities of the pollen grain concentrations?

The set-up of the model, the input data necessary for the atmospheric part of the model, and the pollen-specific constants shall be described below.

3.1. One-dimensional meteorology

In the first application the dispersion of hazel pollen grains was calculated. For this case, homogeneous meteorological conditions were assumed. This means that the meteorological variables could only vary in time and in the vertical direction. Consequently, the mean vertical wind speed equalled zero. The model domain covered an area of $2652 \times 780 \text{ m}^2$ (Figure 1). The horizontal grid size was 78 m in both directions. A line source was located at $x = 702 \text{ m}$. The vertical grid size varied between 1.75 m close to the surface and 245 m at the top of the model domain which was located 3 km above the surface. 25 layers were used in the vertical direction. A 30 days simulation was accomplished with a constant daily cycle of the meteorological variables.

A line source of hazel bushes parallel to the ordinate was assumed with a constant geostrophic wind of 6 m/s perpendicular to the line source. The radiation conditions were chosen according to Julian day 79. The initial relative humidity was 60% at all heights. The vertical temperature gradient in the basic state was 0.8 K/100 m below 1000 m and 1 K/100 m above that height. The pollen-specific parameters necessary to describe the emission, sedimentation, and resuspension fluxes are given in Tables 1 and 2. The meteorological thresholds required for the parameterisations were mostly based on assumptions. The only exceptions were those for the temperature, for which data could be found in literature. The threshold values for resuspension differ from those of emission. Smaller values for the wind speed and higher values for the relative humidity are assumed, because the pollen grains are lying on the ground and not enclosed in the flowers. No low relative humidity is necessary, as no passive dehydration process has to take place prior to emission. Concerning the volume-equivalent diameter d_e , an approach was made with the mean diameter d_p , as Pohl (1937b) had considered the pollen grains of hazel to be spherical. A number of parameters were set equal to one due to the lack of knowledge.

Figure 2a shows the simulated daily cycles of u_* , u_{*le} , and u_{*lr} . Apparently, pollen emission can take place during the daylight hours only. The time period of pollen emission being possible appears to be

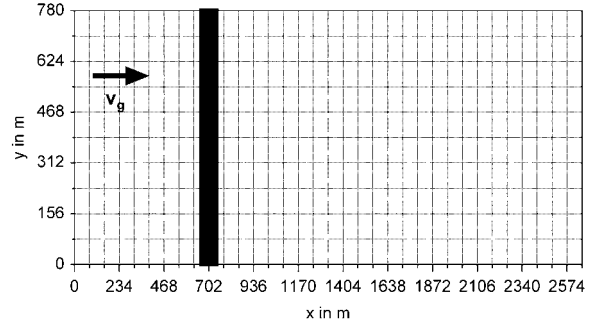


Figure 1. Model domain used for the simulations with the 1-D meteorology. The thick line represents the line source. The arrow gives the direction of the geostrophic wind.

shorter than the time of resuspension being possible. However, it should be kept in mind that most of the threshold values were assumed and are not based on observations.

Figure 2b shows the daily cycles of the vertical pollen source flux for four days of the pollen season. As the meteorological conditions did not differ during these days, the main difference is caused by the temporal development of c_e (equation 4). On day 15 which is in the middle of the assumed pollen season, the maximum pollen flux is $2514 \text{ pollen grains m}^{-2} \text{ s}^{-1}$, while on day 29, the maximum pollen flux is $249 \text{ pollen grains m}^{-2} \text{ s}^{-1}$ only. The difference of the pollen flux between day 1 and day 29 illustrates the effect of the already released pollen grains.

Figure 3a shows daily cycles of the pollen grain concentration at different distances from the source on day 5. The figure gives the results in emission height. Maximum concentration decreases rapidly with increasing distance from the source area.

In the source region the maximum pollen concentration is reached at 12:00 CET. At a distance of 780 m, it is found one hour later due to transport processes. During the night, emission and, hence, pollen concentration drop to zero. Similar daily cycles were measured by Stix and Grosse-Brauckmann (1970) for pollen grains of different deciduous trees, by Zwander (1983) for pollens of the hazel bush, birch, and nettle (Urticaceae), by Jäger (1990) for birch pollen, and by McCartney and Lacey (1991) for oilseed rape pollen. The simulated pollen grain concentrations are much higher than those documented in literature. This is mainly caused by two circumstances. Firstly, a relatively short pollen season was assumed. Secondly, hazel bushes occur as isolated plants rather than in such a dense population as assumed here.

Table 1. Input parameters.

	Hazel		Alder	
	Property	Reference	Property	Reference
q_p in pollen grains/m ²	$1 \cdot 10^9$	Pohl (1937a)	$2.1 \cdot 10^9$	Pohl (1937a)
S in days	30			30
LAI	1			2
h_c in m	5			22
Emission height in m	6			~20
Major and minor principal radius in μm	$a = b = 11$	Helbig (2003)	$a = 12.5$ $b = 13.5$	Pohl (1937b)
d_p in μm	22	Winkler et al. (2002)	29 ^a	
d_d in μm	15.4 ^b			26 ^c
ρ_p in kg/m ³	1008	Pohl (1937b)	752	Pohl (1937b)
ρ_{solid} in kg/m ³	1008 ^d			752 ^d

^aThe mean diameter d_p of alder pollen grains was calculated from water contents measured by Pohl (1937b) and d_d .

^bThe diameter of the dry hazel pollen grains was calculated in the same way, but with d_p .

^cThe diameter of the dry alder pollen grains was chosen to be the arithmetic mean of a and b .

^dAs no other data were available, ρ_{solid} was assumed to be the same as ρ_p .

Table 2. Meteorological threshold values and other parameters.

	Hazel	Alder
T_{te} in $^{\circ}\text{C}$	12 ^a	8 ^a
U_{te} in %	60	60
$ \vec{v} _{te}$ in m s^{-1}	2.4	2.9
U_{tr} in %	85	85
$ \vec{v} _{tr}$ in m s^{-1}	0.9	0.9
c_r	0.7	0.7
c_1, c_2, c_3, c_4, c_5	1	1

^a(Puls, 1985).

Figure 3b shows a cross section of the pollen grain density at 12:00 CET on day 5. The pollen grains mostly remain in the lower layers. Even on day 15 when the highest emission flux occurs, they do not exceed 250 m. This is mainly due to sedimentation of the pollen grains. Therefore, it was concluded from the results of one-dimensional meteorology that the pollen grains were removed relatively rapidly from the atmosphere. It shall be shown in the next section how this behaviour changes when three-dimensional meteorology is taken into account.

3.2. Three-dimensional meteorology

In order to simulate more realistic conditions, three-dimensional simulations were carried out. The model domain included the south-western part of Germany and the adjacent regions (Figure 4a). The horizontal

grid size was $4 \times 4 \text{ km}^2$. 35 layers were used in vertical direction. Here, the grid size differed between 14 m close to the surface and 450 m at the top of the model domain, which was located 8000 m above sea level. A constant geostrophic wind with an east-west component of 1.97 m s^{-1} and a north-south component of 0.5 m s^{-1} was chosen. For calculating the incoming short-wave radiation, Julian day 79 was prescribed. The time steps were of the order of seconds. Figure 4a shows the simulated horizontal wind vectors 20 m above surface at 12:00 CET. The strong modification of the wind field by the inhomogeneous terrain height is obvious. Especially the thermal effects causing the slope winds in the southern part of the Rhine valley lead to a cross-isobar angle of 180 degrees.

In this application the temporal and spatial distributions of alder pollen grains were simulated. In order to determine the flux of pollen grains into the atmosphere, it was necessary to have information on the percentage contribution of alder trees for each grid point of the model domain. Unfortunately, this information was not available. Therefore, it was decided to proceed in the following way. Information was available on the percentage contribution of deciduous forest with a spatial resolution of $30 \times 30 \text{ m}^2$. Moreover, it was assumed that 25% of this deciduous forest consisted of alder trees. Figure 4b shows the result of this procedure. The pollen flux according to equation 1 was scaled with the percentage contribution of alder trees in each surface grid.

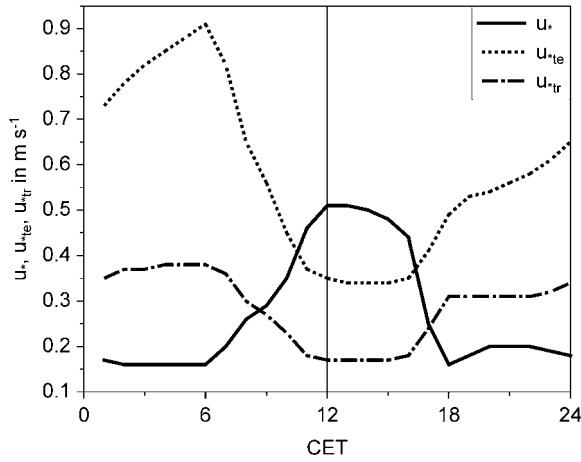


Figure 2a. Daily cycles of u_* , u_{*te} , and u_{*tr} .

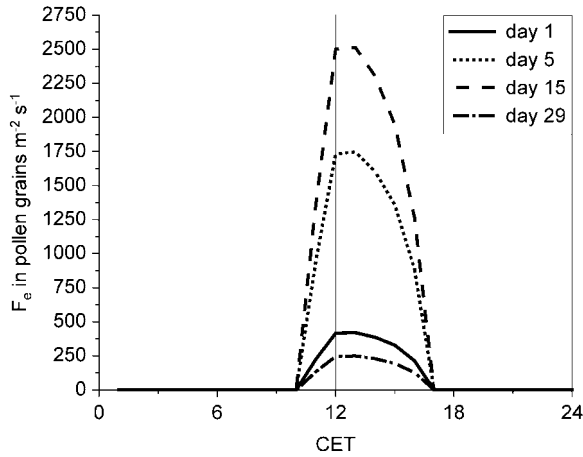


Figure 2b. Daily cycles of F_e for individual days.

The pollen-specific parameters used for alder pollen grains are summarised in Tables 1 and 2. Pohl (1937b) determined major and minor principal radii for the elliptical alder pollen grains. From these, a volume-equivalent diameter of $25.65 \mu\text{m}$ was calculated.

Figure 5 shows the simulated horizontal distribution of u_* , u_{*te} , and u_{*tr} at 12:00 CET. Especially in the south of Karlsruhe, u_* is well above u_{*te} , thus enhancing the emission of pollen grains, while in the mountainous areas u_* is below u_{*te} , as a result of which the emission of pollen grains is suppressed. In contrast to this, u_{*tr} is exceeded by u_* in most areas of the model domain.

Figure 6 shows the emission, sedimentation, and resuspension fluxes of alder pollen grains at 12:00 CET. The highest pollen release is found in the Rhine

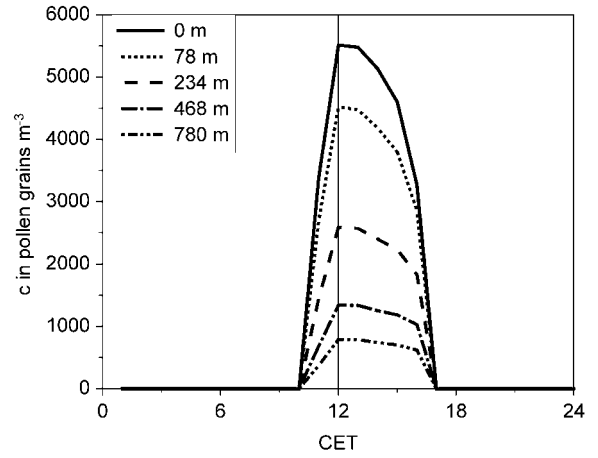


Figure 3a. Daily cycles of the pollen concentration at different distances on day 5.

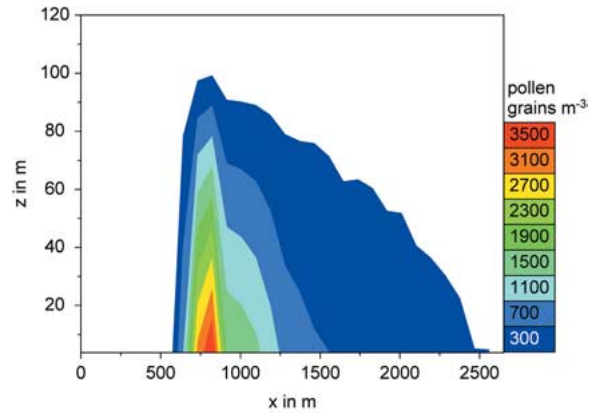


Figure 3b. Cross-section of the pollen concentration at 12:00 CET on day 5.

valley. Although the percentage contribution of alder to the land use is not the highest in the Rhine valley (Figure 4b), the ideal meteorological conditions and, consequently, low values of u_{*te} lead to an enhancement of the emissions in that area. The emission flux is much lower than in the case of one-dimensional meteorology. This is mainly due to the percentage contribution of alder trees in every grid box rather than to the use of uniform area sources. Figure 6b shows the spatial distribution of the sedimentation flux of alder pollen grains close to the surface (in the lowest model layer). At the maximum, it reaches about 10% of the emission flux. At the same time, the resuspension flux is somewhat lower than the sedimentation flux (Figure 6c).

Figure 7a shows the spatial distribution of the alder pollen number density at 12:00 CET close to the sur-

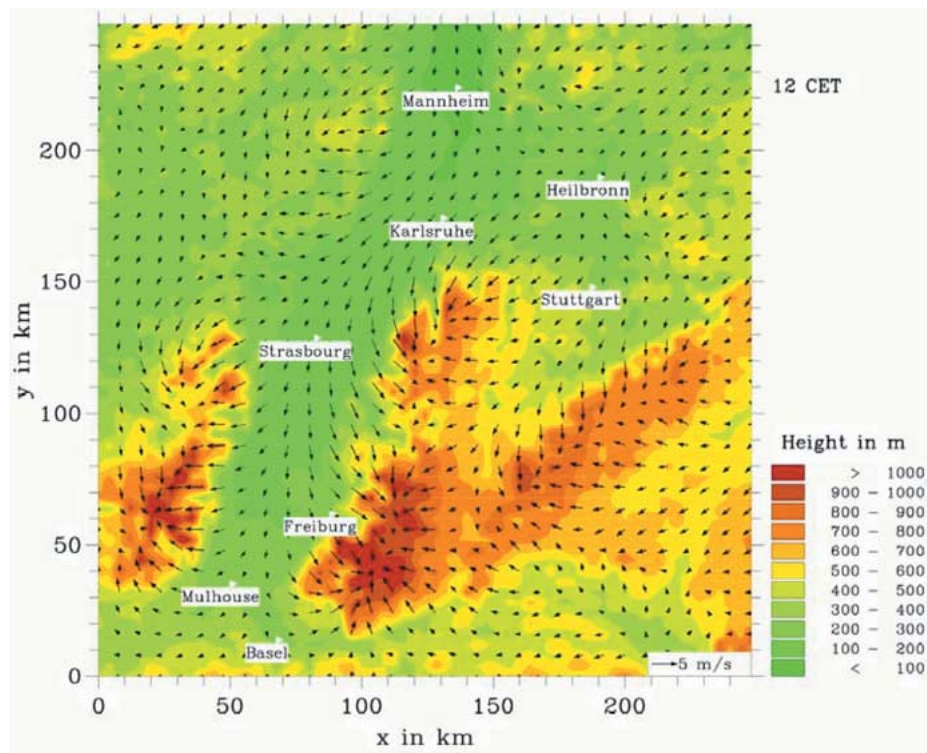


Figure 4a. Topography of the model domain and wind field 20 m above surface at 12:00 CET.

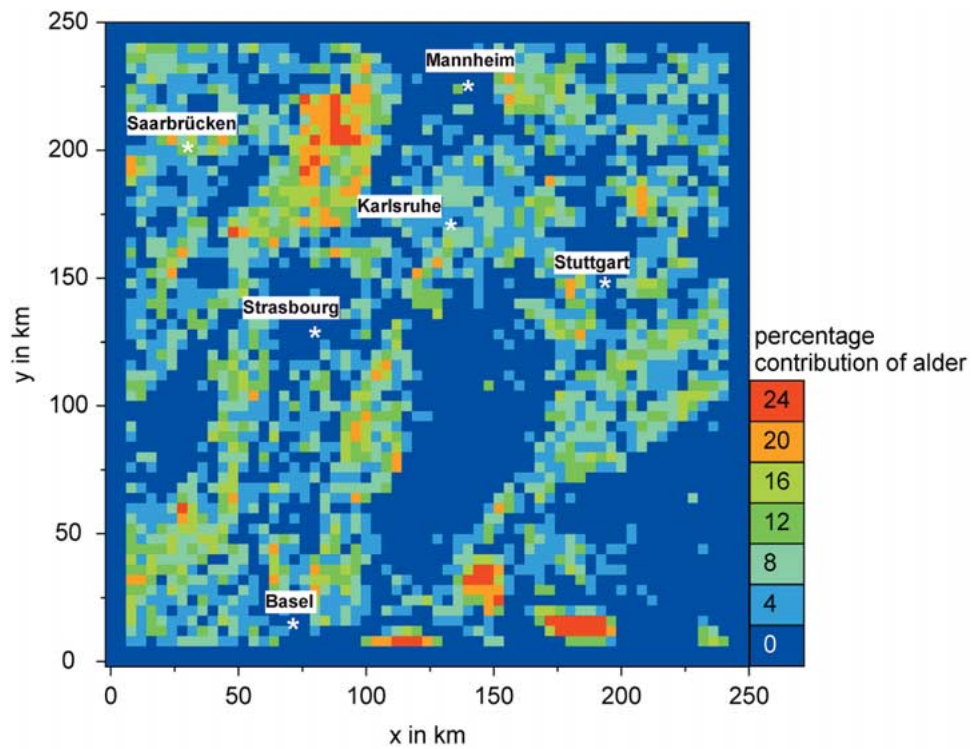


Figure 4b. Percentage contribution of alder in the model domain.

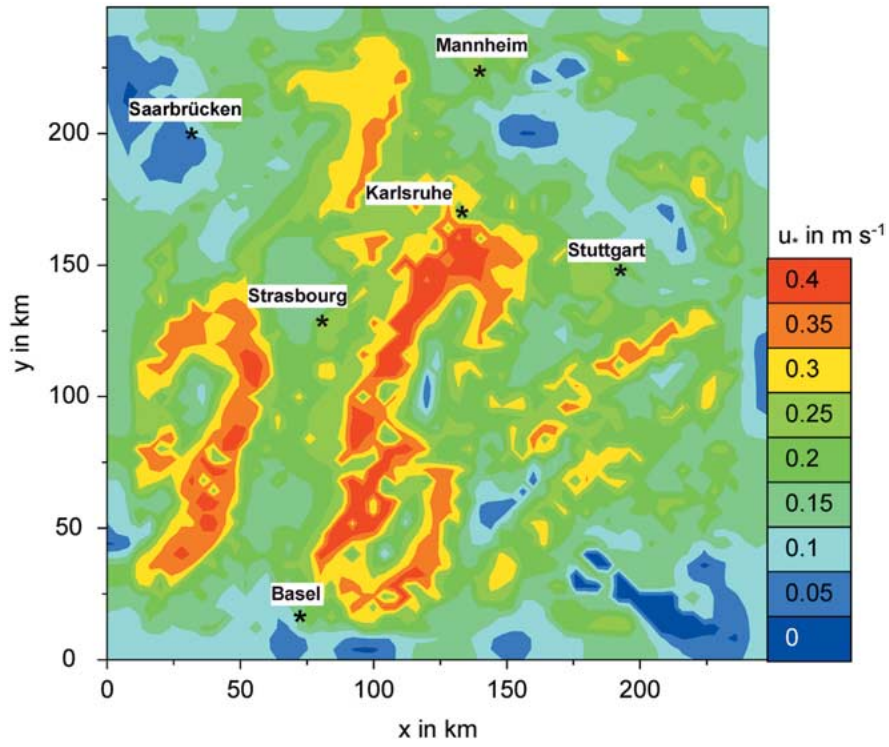


Figure 5a. Horizontal distribution of u_* at 12:00 CET.

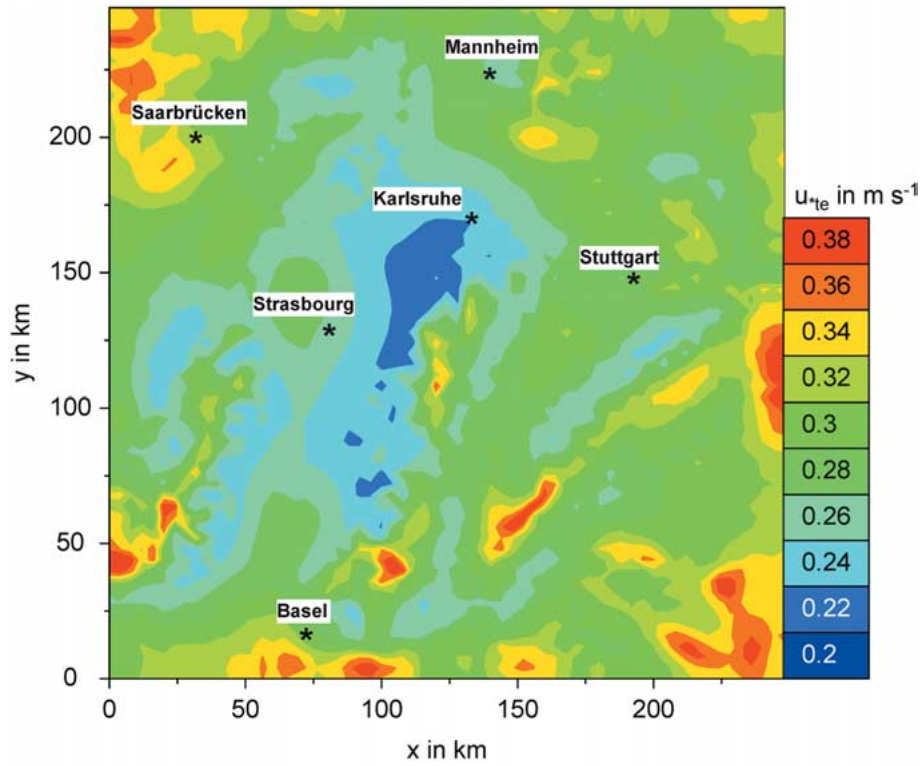


Figure 5b. Same as Figure 5a, but for u_{*te} .

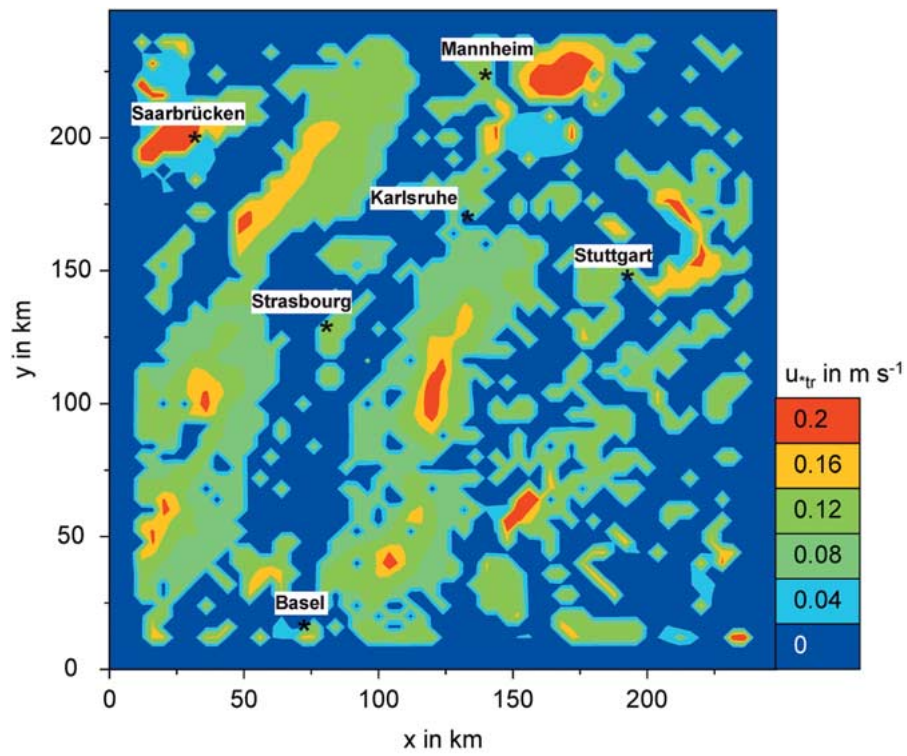


Figure 5c. Same as Figure 5a, but for u_{str} .

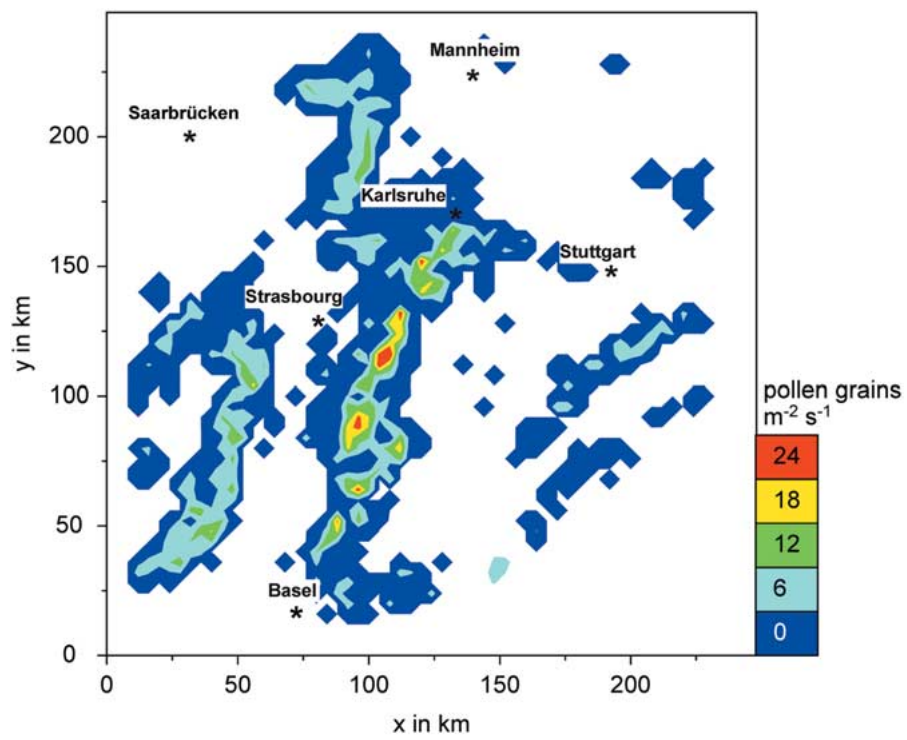


Figure 6a. Horizontal distribution of F_e at 12:00 CET.

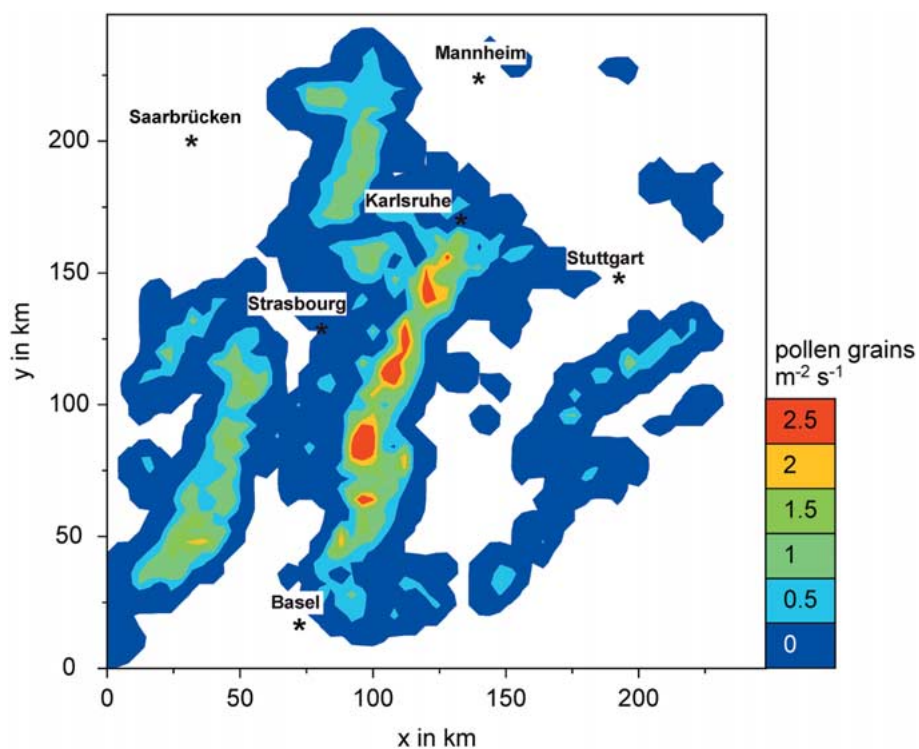


Figure 6b. Same as Figure 6a, but for F_s .

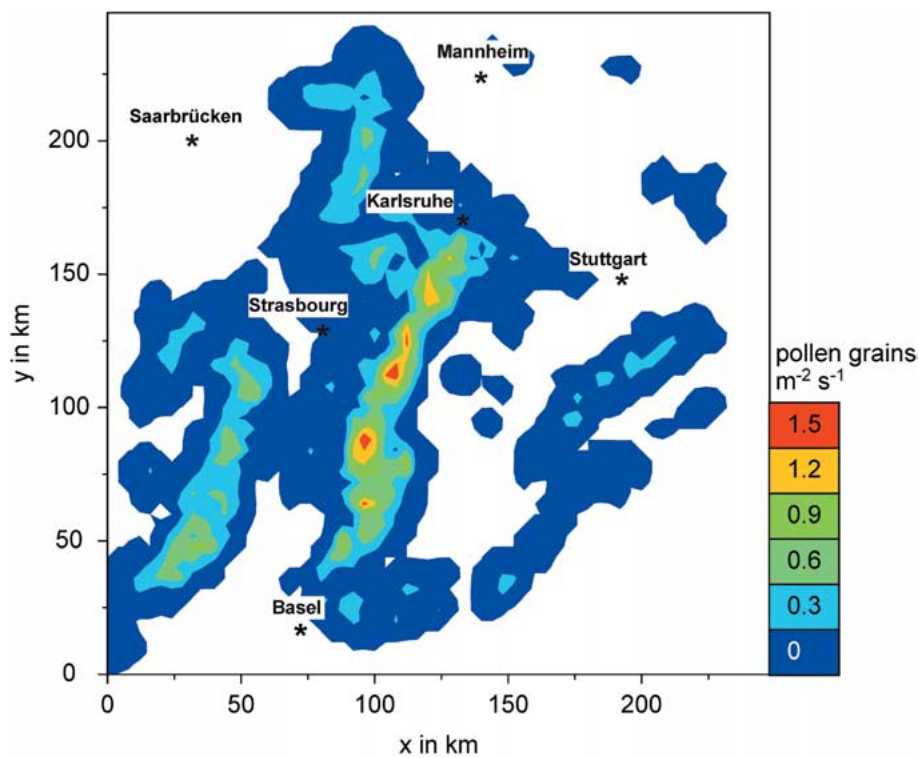


Figure 6c. Same as Figure 6a, but for F_r .

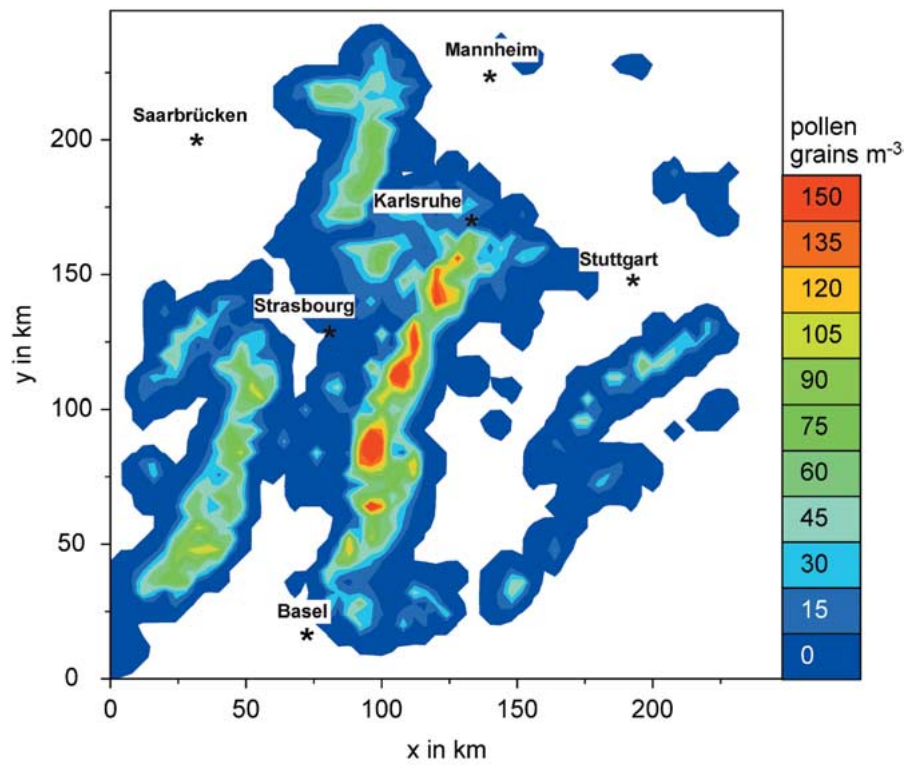


Figure 7a. Horizontal distribution of the pollen concentration about 20 m above the surface at 12:00 CET.

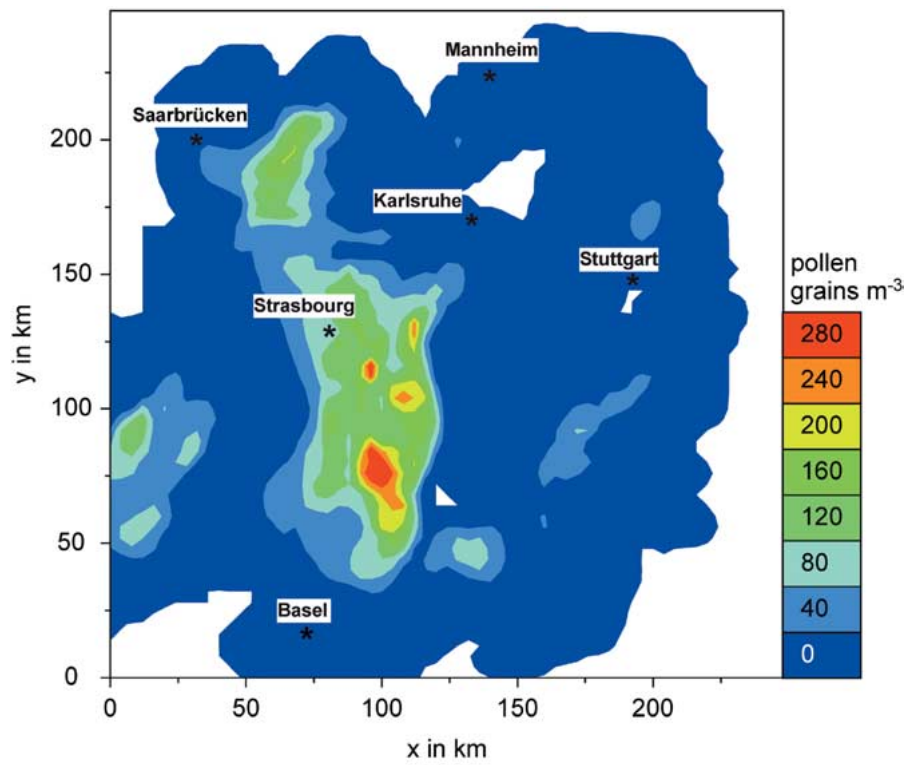


Figure 7b. Same as Figure 7a, but at 18:00 CET.

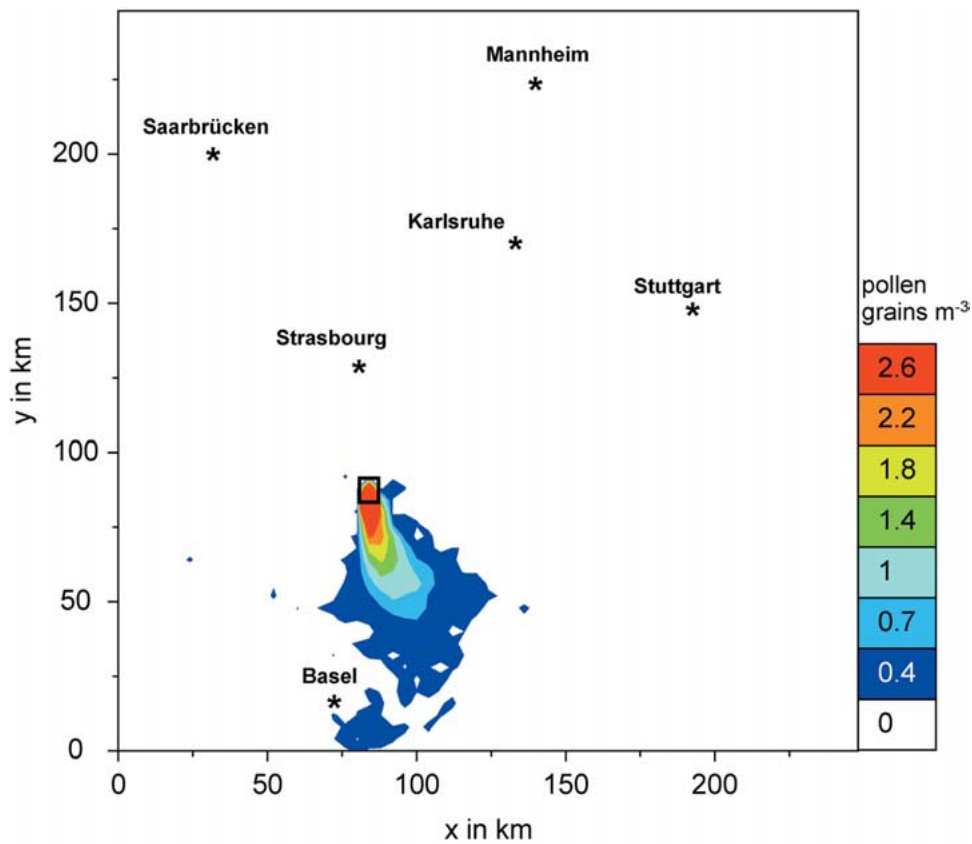


Figure 8. Horizontal distribution of the alder pollen concentration averaged over 36 hours, from 11:00 (day 1) to 22:00 (day 2) CET.

face. As expected, the highest pollen concentrations are found in those areas where the highest emission flux occurs (Figure 6a). At 18:00 CET when the emissions drop down to zero due to the unfavourable meteorological conditions, pollen grains can still be found (Figure 7b). In addition, concentrations reach higher values, and the concentration pattern considerably differs from that of 12:00 CET. It is demonstrated that in the case of the three-dimensional wind field, pollen grains can reach much larger distances from the source regions. This is mainly caused by positive vertical wind speeds which suppress the sedimentation of the pollen grains. Therefore, the atmospheric lifetime of the pollen grains increases remarkably.

Finally, the model system was used to address a question that is important with respect to cross pollination. Only two grid boxes in the area of Freiburg were allowed to release alder pollen grains according to our new parameterisation. Figure 8 shows the resulting average pollen grain number density close to the surface and the marked source grid boxes. The time

interval used for averaging extends from 11:00 CET on day 1 to 22:00 CET on day 2. The concentration distribution shows that a huge area is affected by the emissions, a behaviour that would not be expected judging from the results of one-dimensional meteorology. The distribution is mainly determined by the influence of secondary thermal and dynamic circulation patterns that are induced by the inhomogeneous terrain and land use, respectively. Thus, it is obvious that Gaussian plume models which are often used to address the pollen dispersion of gene-manipulated plants might lead to the wrong conclusions.

Unfortunately, it was impossible to quantitatively compare model results with observations, as such data were lacking. Moreover, it is not an easy task to perform concentration measurements of pollen grains with a high temporal resolution (Ronneberger et al., 2002).

4. Conclusions

New parameterisations were developed and proposed for usage in three-dimensional dispersion models to calculate the emission and resuspension of pollen grains. It was aimed at studying the dispersion of pollen grains by means of methods used in air pollution modelling. These parameterisations which can be used for all kinds of pollen species require a number of parameters that had not yet been measured. Experience shows that there is a need for several kinds of input data to forecast the pollen grain number density in the sense of daily numerical weather forecast. The most important data are pollen production, pollen grain properties (e.g. settling velocity, viability, density, diameter), and plant-specific threshold values. In addition, detailed land use data are necessary. Therefore, a number of assumptions had to be made to apply the new parameterisations in the KAMM/DRAIS model system. Of course, parts of the parameterisations will have to be adapted in the future when adequate measurements might become available.

With these restrictions, the following conclusions can be drawn from the numerical simulation results:

As long as one-dimensional meteorological conditions were assumed, i.e. zero mean vertical wind speed, the pollen grains could travel short distances only. This is in contradiction with findings in literature, which clearly demonstrated that pollen grains can travel over hundreds of kilometres (Rousseau et al., 2003). When switching to a more realistic situation with inhomogeneous terrain and, hence, also spatial variability of the meteorological conditions, the distances that can be travelled by pollen grains increased tremendously. In this case, the pollen grains could be found throughout the whole boundary layer. The results of the three-dimensional simulations have shown that the pollen grain number density is subject to a high spatial variability. It is therefore necessary to replace currently used empirical pollen forecasts, where the hot spots of the distributions cannot be identified by numerical modelling.

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