Mesoscale dispersal of pollen and implications for gene flow

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Paper Content:
In order to better understand long-range dispersal of maize pollen the mesoscale Meso-NH model has been modified to calculate the trajectories and dehydration of pollen grains. Simulations were performed over South-West France during the maize pollination period. As compared with airborne measurements, the model provides good estimates of pollen concentration throughout the atmospheric boundary layer, wheras pollen viability is slightly overestimated. The simulations allow the pollen plume to be characterized on each day and deposition maps of viable pollen to be produced. Our results provide quantification of long-distance pollen deposition and show that background fortitious contamination is unavoidable at regional scale.

Introduction

The growing introduction of genetically modified (GM) crops has generated a host of research efforts aimed at investigating the possibilities for coexistence between GM, conventional and organic farming systems. Published experimental and modelling studies aimed at characterizing pollen dispersal for cultivated species have shown that most pollen grains emitted by a source field deposit within a short distance from the latter, but also that the observed dispersal functions have long fat tails, making it possible for pollen to contaminate plants at rather long distances. Such possibility has been recently confirmed from (i) a series of airborne measurements of maize and oilseed rape pollen concentration and viability in the atmospheric boundary layer, (ii) chamber measurements of maize pollen viability in a large range of temperature and humidity conditions and (iii) observations of fecundations in isolated plots of white-kernel maize, at several km from the nearest maize field (Brunet *et al.*, 2008a and 2008b).

In order to better understand long-range dispersal of pollen it is desirable to investigate the mechanisms by which pollen grains may travel in the atmospheric boundary layer and deposit at long distances from the emission field. Only a few authors interested in pollen from tree species have started to explore this by using mesoscale atmospheric models (e.g., Helbig *et al.*, 2004 for alder pollen; Schueler *et al.*, 2006 for oak pollen). Such modelling exercices have shown that accounting for mesoscale atmospheric motions leads to increasing the travel distance and lifetime of pollen grains, as compared with more classical, shorter-range diffusion models.

Here we focus on maize, a wind-pollinated species of interest in the GM debate, whose pollen grains are particularly large in size (mean diameter about 90 µ) and therefore prone to more rapid deposition. We develop a new modelling approach to simulate the trajectories and dehydration of maize pollen grains in the atmosphere at regional scale. To this purpose the non-hydrostatic mesoscale Meso-NH model has been modified so as to introduce source terms for pollen emission, conservation equations for pollen concentration and moisture, and a deposition velocity.

In a first part we present the atmospheric model. We then introduce the changes made in the model for simulating pollen transport. In a third part we describe how the pollen sources in the region of interest (the Landes region in South-West France) are introduced in the model. A comparison of simulated concentration and viability is then performed against airborne values previously measured over the region. Finally we characterise the pollen plume at the regional scale, in the atmospheric boundary layer as well as in terms of ground deposition.

The atmospheric model

The Meso-NH model was used for this study (version 4-7). Meso-NH is a non-hydrostatic three-dimensional atmospheric model developed by the French research community (Lafore *et al.*, 1998). It allows various characteristics of the atmosphere to be simulated over a range of scales, from low to high resolution. It includes an extensive set of parameterisations covering surface-atmosphere exchanges, boundary-layer turbulence, cloud microphysics, convection, radiation, etc. Turbulence is modelled with a k-l closure scheme and includes the resolution of a prognostic equation for turbulent kinetic energy (Bougeault and Lacarrère, 1989).

Surface fluxes of sensible heat, latent heat and momentum are solved by the ISBA model (Noilhan and Mahfouf, 1996). Microphysics and radiation transfer are modelled by a Kessler-type parameterisation and the ECMWF model, respectively. Meso-NH also includes a chemistry code allowing the transport of gases and aerosols to be coupled with the dynamics. Numerous diagnostic tools have been developed in the model in order to facilitate the comparisons with surface and airborne measurements as well as satellite observations.

The present study has been performed over the Landes area in the Aquitaine region (South-West of France). To a large extent, this area is a mixture of pine forests and maize fields, extending over about 10 000 km². It displays very gentle topography. In our simulations the meteorological fields are solved over three nested domains covering Western Europe, South-West France and Aquitaine, respectively (Figure 1). On the vertical the atmosphere is discretised in 48 levels, 32 of them being within the atmospheric boundary layer, between 0 and 2500 m. The meteorological fields are initialised from the large-scale weather forecast model ARPEGE. The latter also provides the lateral boundary conditions for the largest domain.

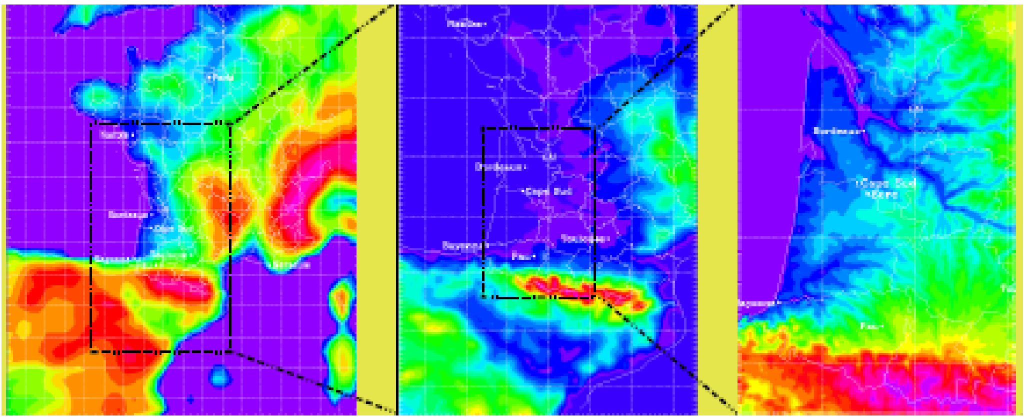

Figure 1. The three nested atmospheric simulation domains. From the left to the right the horizontal resolution is 32, 8 and 2 km, respectively. The largest domain covers part of Western Europe, the intermediate one includes parts of France and Northern Spain and the smallest one focusses on the Aquitaine region. The colours are indicative of the topography.

Modelling pollen transport

The dispersal of pollen grains has been introduced in Meso-NH through conservation equations written in an Eulerian framework. Here we are interested not only in the amount of pollen transported by the atmosphere, but also in the time variation of its viability. We therefore have to calculate its dessication rate since pollen viability is primarily driven by its water content (Fonseca and Westgate, 2005; Aylor, 2003). The latter authors showed that its viability becomes very small when the water content reaches 30%. This value will be considered here as the lethal threshold.

Consequently, four conservation equations were introduced: two for the concentration in alive and dead pollen and two for the water content of alive and dead pollen. Regarding alive pollen for example, these equations take the following form:

$$\partial C_a / \partial t = adv + turb + grav - T_{a \to d}$$

and

$$\partial W_a / \partial t = adv + turb + grav - T_{a \to d} - E_p$$

where C_a is the concentration in alive pollen (N grains m^{-3}), W_a the amount of water in the living pollen grains (kg m^{-3}); *adv*, *turb* and *grav* are the terms representing the transport by advection, turbulence and gravity; $T_{a \to d}$ represents the pollen death rate; E_p is the evaporation flux from pollen grains.

In the present version of the model the terms *grav*, $T_{a \to d}$ and E_p are calculated from Aylor (2002) and Aylor (2003). The gravity term is then proportional to $V_s(\theta)$ where V_s is the sedimentation velocity, that depends on pollen moisture θ; $T_{a \to d}$ is proportional to $dG(\theta)/dt$ where G is the germination rate; E_p is proportional to the pollen grain surface area $A(\theta)$ and to the difference in relative humidity $h_p(\theta)-h_a$ between the evaporating surface and the air.

In order to simulate pollen transport with Meso-NH we also need to quantify pollen fluxes at the ground. This requires the localisation of all sources to be known and a time-varying emission rate to be prescribed.

Mapping regional pollen sources

In order to locate all maize fields over the region we used four satellite images at two key dates of the maize cycle:

- two SPOT5 images taken on May 30, 2003, covering a subregion of 68 x 75 km² at a 10 m resolution;

- two SPOT2 images taken on July 19, 2003, covering a subregion of 61 x 110 km² at a 20 m resolution.

All images were processed in a Lambert 3 format within a geographical information system. The work consisted in four steps: (1) initial mapping of reference fields, representative of the various landuse types; (2) image processing using recognition algorithms based on the multispectral distribution of the radiometric properties of each field; (3) multidate combination of the images ; (4) validation of the results over a set of fields indentified on the ground. The final multidate image displays 14 classes.

Figure 2 shows the resulting location of all maize fields over the Landes region, a subregion of Aquitaine. The validation step shows that this evaluation is correct (97.5 % success rate). This map was later degraded down to the 2 km resolution of the smallest MesoNH domain, so that a fraction of maize area could be attributed to each grid cell.

During the flowering period, pollen emission exhibits strong daily and hourly variations, that appear to depend on microclimatic factors such as radiation, wind speed, temperature and humidity (Marceau *et al.*, 2008). These authors have attempted to parameterise the effect of each factor on the emission rate. However in the present version of our model we simply assume that the emission rate displays a Gaussian hourly variation, that reaches its maximum at 12h UTC and has a width of

6 hours at half the maximum emission rate. The latter is then the only parameter of this simple scheme.

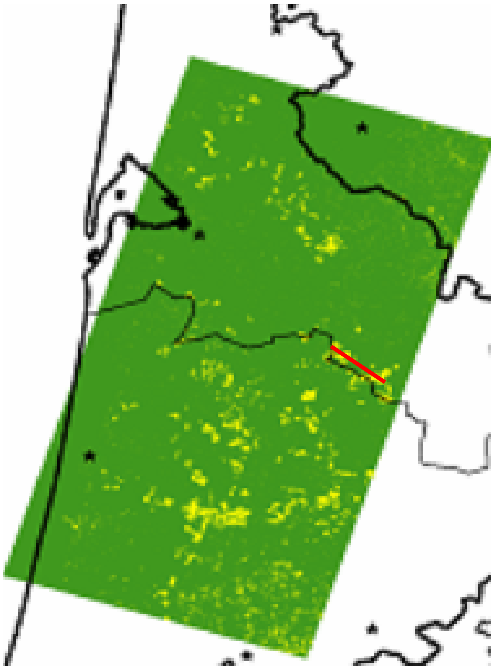

Figure 2. Map of all maize fields over the Landes region in Aquitaine, as estimated from the 2003 SPOT images. The red line shows the flight paths used to test the model.

Comparison with airborne measurements

A first test of the model was performed for a particular day (July 12, 2003). On this day airborne measurements of pollen concentration and viability had been carried out throughout the boundary layer at three times: 9 h UTC (4 altitudes), 12 h UTC (7 altitudes, up to 1800 m) and 16 h UTC (5 altitudes). The flight path (about 10 km) is shown in Figure 2. At all times all variables of interest were extracted from the MesoNH outputs along the flight path, so that it was easy to compare directly simulated and measured pollen concentration and viability.

Figure 3 shows the vertical variation in simulated and measured pollen concentration on July 12, 2003. As the actual emission rate over the region was unknown, the maximum rate was adjusted so as to minimize the differences observed during the second flight (11 grains m^{-2} s^{-1}), and all maize fields were assumed to emit pollen at a similar rate. Figure 3 shows that the model provides a fairly good estimation of the measured concentrations at all heights throughout the day. These vertical profiles are typical of a convective boundary layer. The latter grew up to about 1600 m on this particular day, allowing pollen to be entrained up to this height.

The results are less good for pollen viability (Figure 4): the simulated viability appears too large during the day, as if the modelled pollen grains were not dehydrating at a faster enough rate or in other words as if their evaporation rate were underestimated. This result is in good agreement with our finding that the model of Aylor (2003) used in this simulation does not fit well with our own data on pollen dessication (Brunet *et al.*, 2008b). We indeed allowed samples of fresh pollen grains to dehydrate in a ventilated climatic chamber for a range of air temperature and humidity; the measured pollen water content decreased at a faster rate than that predicted by Aylor (2003). An new model for pollen dessication was then developed (not shown here), which should lead to an improvement of the simulation results.

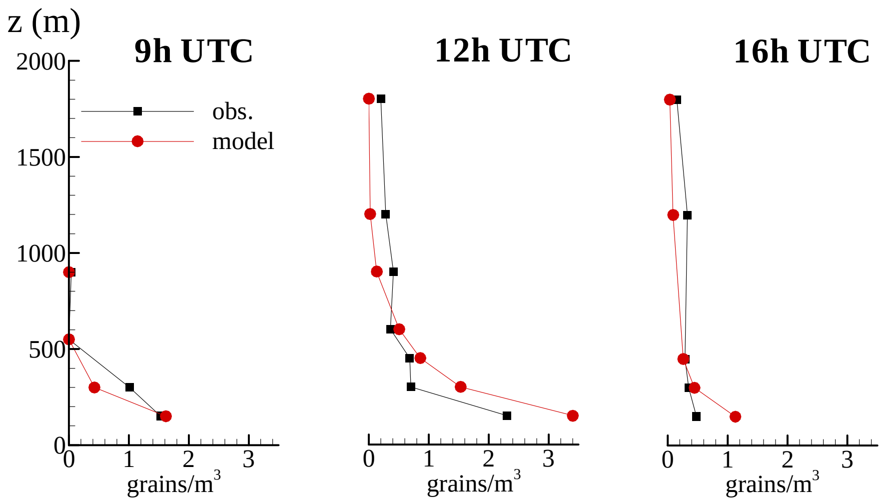

Figure 3. Vertical variations in maize pollen concentration in the boundary layer on July 12, 2003, measured from air samples taken aboard a light aircraft (see Figure 2 for the location) and simulated by MesoNH.

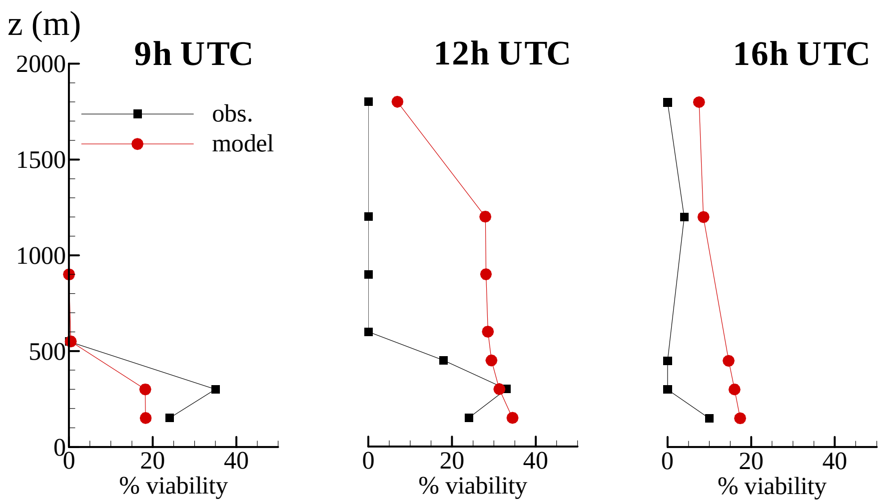

Figure 4. Vertical variations in maize pollen viability in the boundary layer on July 12, 2003, measured from air samples taken aboard a light aircraft (see Figure 2 for the location) and simulated by MesoNH.

Simulated regional pollen dispersal

Figures 5 and 6 show the plumes of pollen concentration and viability, as simulated over the whole region, at three times and two altitudes (500 m and 1200 m).

Figures 5 shows that the pollen plume moves towards the West on this particular day (easterly wind). The results generalize at the scale of the region the local results shown in Figures 3 and 4. One can clearly see how pollen moves upwards during the day, and reaches a maximum concentration in the middle of the day. The extent and heterogeneity of the plume reflects those of the source fields, with some dilution caused by the atmospheric motions and transport. The weight of the Southern region that exhibits a large number of fields (see Figure 2) is clearly visible on the plume. This region generates small areas of relatively high concentration (> 1 gr m^{-3}) visible at 1200 m at 12 h in the South-West part of the domain. Such high values were not observed at the location of the flights further to the North-East (see also Figures 2 and 3).

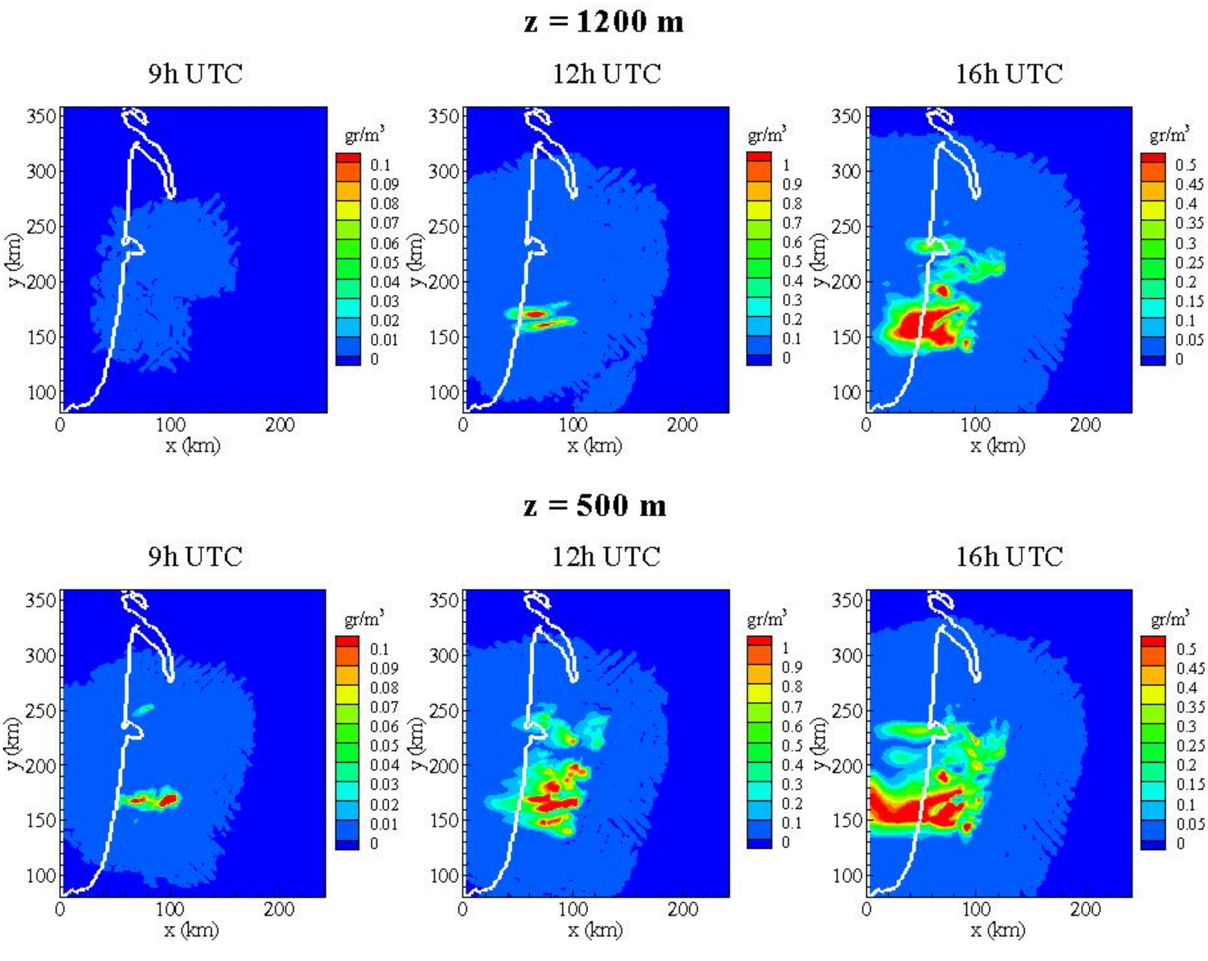

Figure 5. Simulated plume of pollen concentration over the region, at 500 m et 1200 m and at three times (July 12, 2003).

Pollen viability appears spatially heterogeneous. At any given time and height, the plume show both regions of low viability and regions of relatively high viability (> 20%). Even at 16 h and 1200 m, small areas of high viability can be seen.

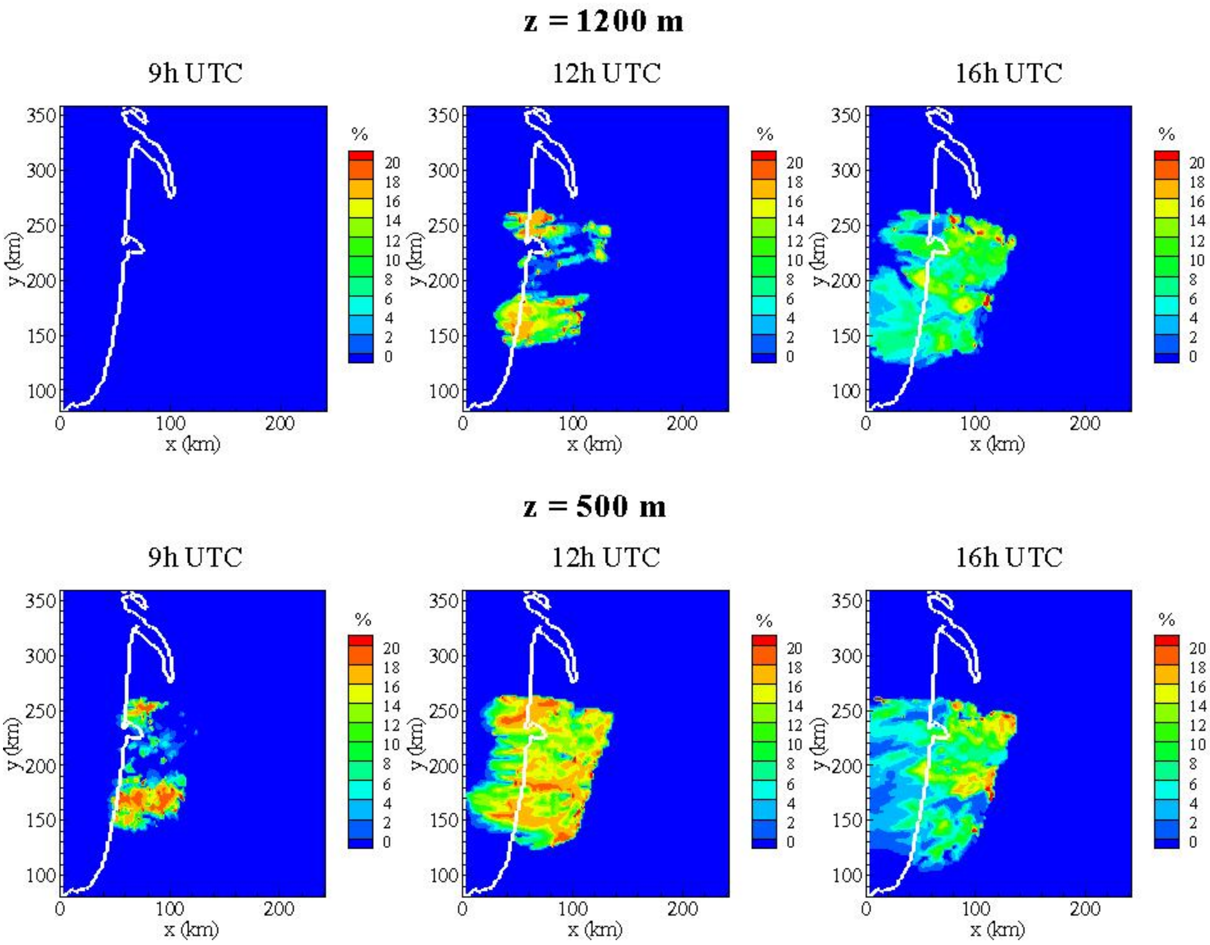

Figure 6. Simulated plume of pollen viability over the region, at 500 m et 1200 m and at three times (July 12, 2003).

What matters more than the atmospheric concentration and viability, in terms of fortuitous cross-pollination, is the surface deposition of viable maize pollen. Figure 7 shows the deposition of viable pollen, accumulated over the whole simulated day. Several features are visible on this figure:

- regions (in red) with "high" deposition (> 1 grain m^{-2}) over or nearby maize fields ;

- regions (in orange and yellow) with smaller deposition that remain significant over relatively large areas, at some distance of the closest maize fields (several km); these regions reveal the presence of "background levels" of deposited maize pollen at such distances from the fields that the presence of pollen cannot be expected from local-scale diffusion models, or from the extrapolation of local measurements performed downstream from maize fields;

- regions (in green and blue) outside of the set of maize fields (e.g. in the South), showing a steady decrease of pollen deposition at a rate of about a factor 10 per 15 km.

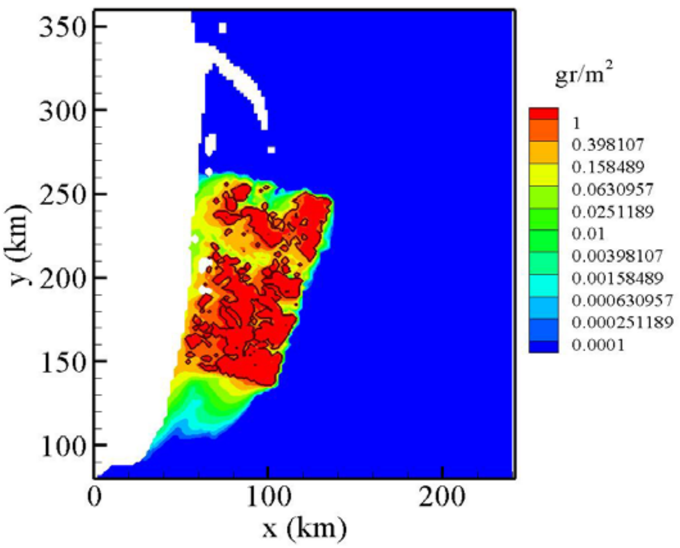

Figure 7. Map of accumulated deposition of viable pollen grains (number of grains m^{-2}) over one day during the pollination period (July 12, 2003), as simulated by the Meso-NH model.

Conclusions and perspectives

A modelling tool based on atmospheric mesoscale modelling and remote sensing has been developed to simulate pollen emission, transport and deposition at regional scale. The model was successfully tested for its ability to predict pollen concentration throughout the atmospheric boundary layer at various times of the day. The time variation in pollen viability was not simulated with such accuracy, but recent results obtained in a climatic chamber should lead to a significant improvement. More days with airborne measurements are available for a further validation of the numerical code.

The present results on the regional dispersal of maize pollen confirm the experimental evidence collected over the past few years, showing that it can be transported, will remaining viable to a significant extent, at larger distances than was previously thought. The map of daily accumulation of viable pollen provided here reveals the existence of a background deposition level, even at large distances from the nearest fields. This confirms and extends the results of Helbig *et al.* (2004) that were acquired with smaller and lighter pollen grains.

Such results may provide an explanation for the existence of long fat tails in the spatial distribution of cross-contamination from source fields, that local diffusion models do not normally predict. We now need to investigate the deposition patterns in a more quantitative way, i.e., estimate values of pollen deposition over a range of climatic conditions, landuse configurations and management practices. Beyond this, we also have to find ways to convert deposition rates of viable pollen into effective risks of cross contamination, in order to quantify the implications of large-distance pollen flow for actual gene flow.

Acknowledgements

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