Simulation of the Effect of a Cornfield on Wind and on Pollen Deposition

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Abstract: Pollen deposition was measured inside and outside of a cornfield throughout the flowering season. Weather conditions, such as temperature and wind speed distribution around the cornfield, were measured simultaneously. In order to clarify the effects of the cornfield on the flow, a three-dimensional numerical model for simulating wind distribution over complex terrain was used, by treating the cornfield as a type of tableland. The three-dimensional, time-dependent Navier-Stokes equation written with generalized coordinates and the Smagorinsky-type scheme for turbulent parameterization were used in the model. Simulation results were in good agreement with observations of wind speed, showing that there was an attached re-circulation bubble with much lower wind speed in the lee edge of the cornfield. Pollen deposition decreased exponentially with distance from the edge of the cornfield. An extremely large amount of pollen was deposited near the edge due to wind reduction there.

Keywords: Air flow Cornfield Pollen deposition Turbulent parameterization

1. INTRODUCTION

Corn pollen can be dispersed over 60 meters out of a cornfield by wind [Raynor et al., 1972a]. Losey et al. [1999] has shown that Bt (*Bacillus thuringiensis*) corn plants might represent a risk to non-target organisms because most hybrids express the Bt toxin in pollen. However, Losey et al. did not investigate the amount of pollen changing with its deposition distance. There have been many research works on pollen deposition and dispersion [e.g. Raynor et al., 1972a, 1972b, 1973; Chamberlain, 1975; Price and Moore, 1984; Giddings et al., 1997a, 1997b]. However, none of them had examined the relationship between pollen deposition and meteorological conditions in detail. Gaussian diffusion model had been used for simulating the multi-point source of pollen emission and dispersion [e.g. Raynor et al., 1973]. However, wind in the model was uniformly distributed within the domain. Wind distribution effect on pollen deposition, especially the effect of the cornfield itself on wind and deposition has not been introduced. In order to clarify the effects of the cornfield on wind and pollen deposition, field observation of pollen deposition and wind conditions were carried out during the summer of 1999 and 2000 and a simple numerical model [Du et al., 1997] to simulate the mean air flow over and near a cornfield has been used. This paper tries to clarify the effect of the cornfield on wind distribution and pollen deposition.

2. METHOD

2.1 Observation

In order to clarify the distribution pattern of corn pollen deposited around a cornfield and the effect of the meteorological conditions on the deposition, observations of the amount of pollen deposition in the leeward side of a cornfield and meteorological elements were carried out in the flowering season of corn in 1999 and 2000.

2.1.1 Case in 1999

Figure 1 shows the site and observation points. 10 minutes mean wind speed 1m above the ground or zero-plane displacement (here we take 1m, that is about 2/3 of corn height) was measured at 5 points along the central line: S (10m to south), C (cornfield), N2 (2m to North), N10 (10m to North) and E2 (2m to East) as shown in Figure 1. Air temperature and humidity were also measured at C. Daily pollen deposition was measured at 1m above the ground by putting microscope slides on 10

Durham samplers at S10, S2, C, C2, N2, N10 and E2. Collected pollen grains were counted using a microscope. For experimental details see Kawashima et al. [2000].

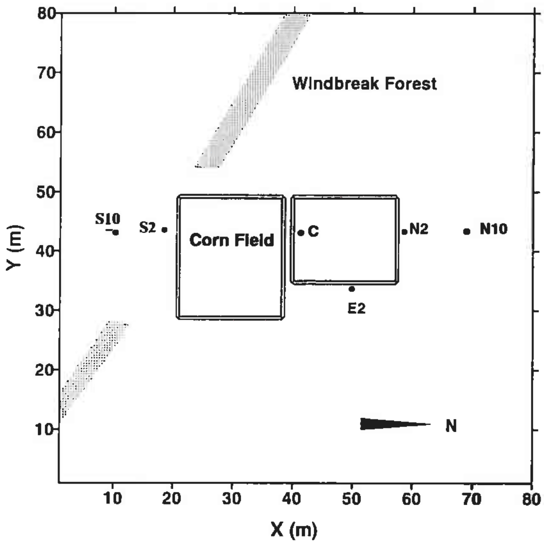

Figure 1. Description of the field in 1999.

2.1.2 Case in 2000

Figure 2 shows the site and observation points. 10 minutes mean wind speed 1m above the ground was measured at each point as shown in Figure 2 by moving measurement. 10 minutes mean wind speed 1m above the ground at an open place and at point W10 (10m from the cornfield at W line as shown in Figure 2) for data comparison and correction were also measured during the flowering season. Daily pollen deposition was measured at 1m above the ground by putting microscope slides on Durham samplers at each point. Collected pollen grains were counted using a microscope.

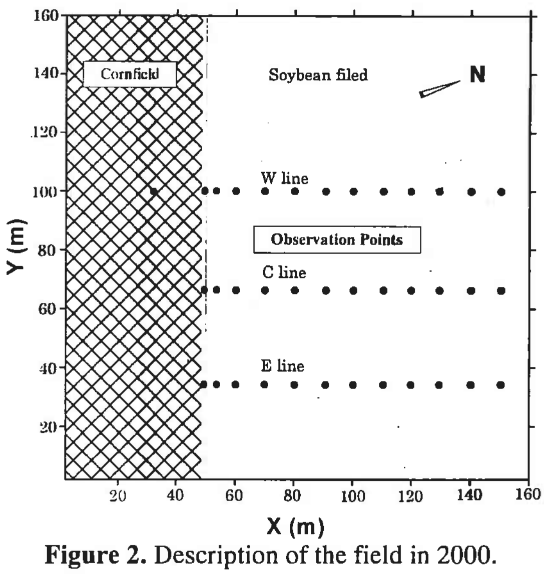

Figure 2. Description of the field in 2000.

2.2 Numerical Simulation

2.2.1 Model

By treating the cornfield as a type of tableland, a three-dimensional numerical model for simulating wind distribution over complex terrain [Du et al., 1997] can be used. In the model, we consider that the height variation of complex terrain (here the cornfield) is less than 10m so that the effect of the Coriolis force and thermodynamic variation induced by cornfield may be neglected. Only neutral stratification was considered. In order to catch the influence of sharp variation of the edge of the cornfield and topography, generalized terrain-following coordinates (ξ, ψ, ζ) were used, defined as follows. The vertical line ζ is orthogonal to the ground surface and $\zeta=0$ is at the ground surface, and the ξ, ψ coordinate lines are orthogonal to the vertical coordinate line. Thus, under the Boussinesq approximation, the three-dimensional, non-hydrostatic, incompressible atmospheric continuity equation and equations of motion in the generalized terrain-following coordinates (ξ, ψ, ζ) may be written as

$$\frac{\partial(U/J)}{\partial\xi}+\frac{\partial(V/J)}{\partial\psi}+\frac{\partial(W/J)}{\partial\zeta}=0 \tag{1}$$

$$\frac{\partial(u_i/J)}{\partial t}+\frac{\partial(Uu_i/J)}{\partial\xi}+\frac{\partial(Vu_i/J)}{\partial\psi}+\frac{\partial(Wu_i/J)}{\partial\zeta}$$
$$=-\frac{\partial(\xi_i P/J)}{\partial\xi}-\frac{\partial(\psi_i P/J)}{\partial\psi}-\frac{\partial(\zeta_i P/J)}{\partial\zeta}+\frac{\partial((\xi_x\tau_{i1}+\xi_y\tau_{i2}+\xi_z\tau_{i3})/J)}{\partial\xi}$$
$$+\frac{\partial((\psi_x\tau_{i1}+\psi_y\tau_{i2}+\psi_z\tau_{i3})/J)}{\partial\psi}+\frac{\partial((\zeta_x\tau_{i1}+\zeta_y\tau_{i2}+\zeta_z\tau_{i3})/J)}{\partial\zeta}$$

(i=1, 2,3; $u_i = u_1, u_2, u_3$ = u, v, w, while

$\xi_i = \partial\xi/\partial x$, $\partial\xi/\partial y$, $\partial\xi/\partial z$ etc.) (2)

where U, V, W are the velocity components in the generalized terrain-following coordinates (ξ, ψ, ζ), u, v, w are the velocity components in the Cartesian coordinates (x, y, z), ξ_x, ξ_y, ξ_z, ψ_x, ψ_y, ψ_z and ζ_x, ζ_y, ζ_z are derivatives with respect to the subscript and $J = \xi_x\psi_y\zeta_z + \xi_y\psi_z\zeta_x + \xi_z\psi_x\zeta_y - \xi_z\psi_y\zeta_x - \xi_y\psi_x\zeta_z - \xi_x\psi_z\zeta_y$ is the Jacobian for the transformation between the two coordinate systems. $P=p/\rho_0$ is air pressure, ρ_0 is the air density, and τ_{ij} (i, j=1, 2, 3) is the trace-free subgrid-scale Reynolds stress. The Smagorinsky-type subgrid scheme [1963] is used in our model, considering the balance between shear production and dissipation by topography and cornfield. Thus, we have subgrid-scale Reynolds stress in the generalized terrain-following coordinates (ξ, ψ, ζ) as follows.

$$
\begin{aligned}
&\tau_{ij} = \nu \cdot D_{ij} \\
&D_{ij} = (\xi_i \cdot \frac{\partial u_j}{\partial \xi} + \psi_i \cdot \frac{\partial u_j}{\partial \psi} + \zeta_i \cdot \frac{\partial u_j}{\partial \zeta} + \xi_j \cdot \frac{\partial u_i}{\partial \xi} + \psi_j \cdot \frac{\partial u_i}{\partial \psi} + \zeta_j \cdot \frac{\partial u_i}{\partial \zeta} \\
&\nu = (C_s \Delta)^2 (0.5 \sum_{i,j=1}^{3} D_{ij}^{\ 2})^{1/2} \\
&\Delta^3 = (\Delta x \Delta y \Delta z) = (\Delta \xi \Delta \eta \Delta \zeta) / J \\
&C_s = 0.12
\end{aligned}
\qquad (3)
$$

where ν is the turbulent exchange coefficient, and C_s is called as Smagorinsky constant. At the surface boundary, we assume that neutral stratification can be applied to ζ axis. The boundary conditions are defined as follows:

At ground surface:
u=v=w=0,
$\partial P / \partial \zeta = 0$
At the top of the domain:
$\partial u/\partial \zeta = \partial v/\partial \zeta = \partial w/\partial \zeta = \partial P/\partial \zeta = 0$
At the in-flow boundary:
u=u0, v=v0, w=w0,
$\partial P / \partial \zeta = 0$
At the out-flow boundary:
$\partial u/\partial \zeta = \partial v/\partial \zeta = \partial w/\partial \zeta = \partial P/\partial \zeta = 0$

Details about the transformation of coordinates, parameterization, grid formation and numerical aspects of the model are given in Du et al. [1997] and Takahashi et al. [1998].

2.2.2 Simulation

The horizontal grids were 80*80 by interval of 1m in case of 1999 and 2m in 2000. Vertical level was ten (include surface level) and the upper limit of the domain is 9m. The windbreak shown in Figure 1 was ignored. Zero-plane displacements (2/3 of heights of the cornfield) were treated as tablelands, which were 0.8m in 1999 and 2.2m in 2000.

The initial wind was 5.0 m/s to the field. That is u_0=5.0m/s, v_0=w_0=0 and u_0= -5.0m/s, v_0=w_0=0. Time interval was 0.1s. The results of 2,000 steps or after 3 minutes and 20 seconds, when a stationary flow field was obtained, were used for the evaluation.

3. RESULTS

3.1 Effect of Cornfield on Wind Distribution

3.1.1 Horizontal wind

Simulation shows that a cornfield can effect horizontal wind distribution very greatly. There is an area of very weak wind just behind the leeward edge of the cornfield as shown in Figures 3 and 4. Wind speed is reduced even 80% in the center of the weak wind area. The wind distribution pattern on the observation line is in good agreement with observation data as shown in Figure 4. Simulation can give a more detailed wind distribution than observation.

3.1.2 Vertical wind

Figure 5 shows the vertical cross-section of wind vectors and Figure 6 shows the vertical cross-section of wind speed passing over the central line along the X direction for the field in 2000. It is clear that an attached recirculating bubble behind the leeward edge of the cornfield appears and a wind reduction region exists within 20m to the leeward edge. The height of the cornfield plays an important role on the wind distribution, which is very similar to that of a windbreak [Wang and Tatle, 1995, Takahashi et al., 1998] or a building [Murakami and Mochida, 1987 and 1988; Paterson and Apelt, 1990].

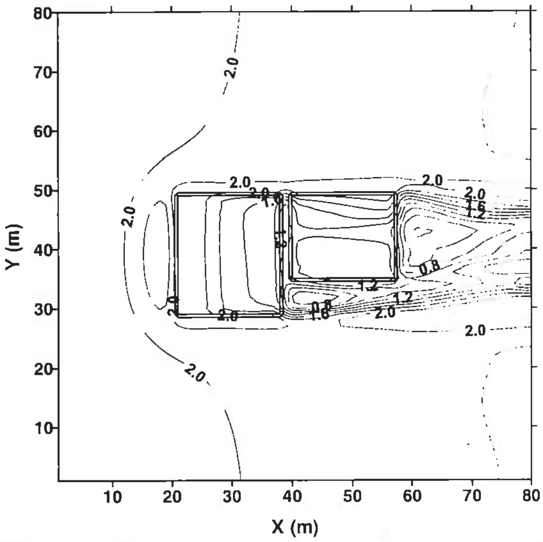

Figure 3. Horizontal distribution of wind speed of first level (0.9m above the ground or cornfield) for the field in 1999, when 5m/s south wind flows to the domain.

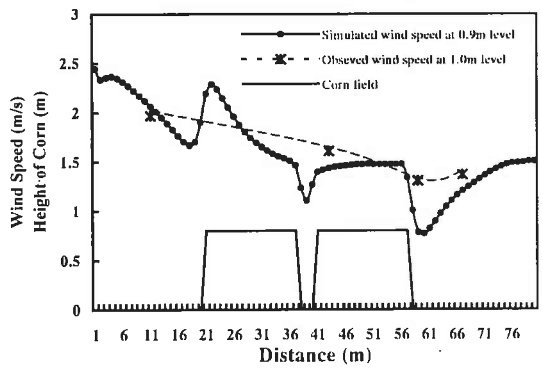

Figure 4. Wind distribution on the central line (calculated and observed) for the field in1999.

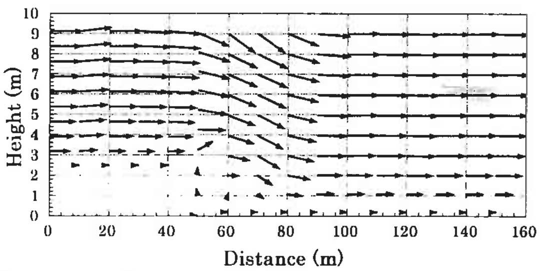

Figure 5. Vertical cross-section of wind vectors over the central line along the X direction (W line as shown in Figure 2).

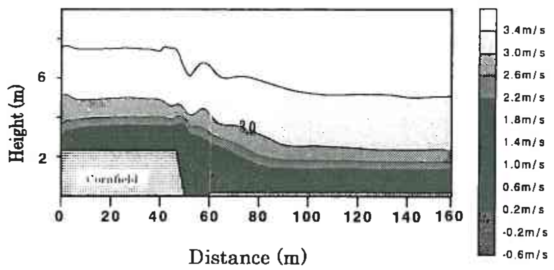

Figure 6. Vertical cross-section of wind speed passing over the central line along the X direction (W line as shown in Figure 2).

3.2 Effect of Wind Distribution on Pollen Deposition

Figure 7 presents observed horizontal variation of relative pollen deposition (normalized by deposition amount inside the cornfield) and relative mean wind speed (normalized by wind speed in an open space) with distance in the leeward side of a cornfield obtained in 2000. The amount of pollen deposition within the distance of 0-20m from cornfield was very high and decreased very quickly, while the wind speed there was much lower. After 20m from the cornfield, pollen deposition showed an exponential decrease with distance, while wind speed changed not so much compared with that between 0-20m. Chamberlain [1975] has pointed out that dispersion of small pollen like ragweed and timothy follows a $x^{-0.875}$ law (where x is the distance from the field) and the loss by deposition is not great enough to steepen the gradient appreciably compared with theory and that big pollen like corn has a more rapid decrease with distance. We suggest that this rapid decrease is not only because the corn pollen is bigger than others, but also because the cornfield has a great effect on the wind distribution as described above. The effect of the cornfield on pollen deposition and dispersion is very similar to that of a cube or building as simulated by Dawson et al. [1991] and Zhang et al. [1993].

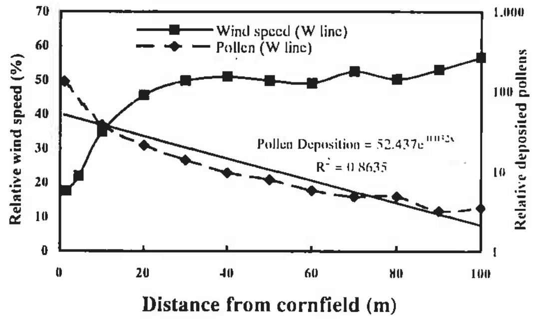

Figure 7. Horizontal variation of relative pollen deposition and mean wind speed in the leeward side of the cornfield (W line as shown in Figure 2).

4. CONCLUSION AND DISCUSSION

There is a significant effect of cornfield on wind distribution due to its high density and height. Wind near the leeward edge is very weak or even reversed. This reduction of wind speed and / or change of wind direction allows a huge amount of corn pollen deposition near the edge of the cornfield, otherwise, the distribution of pollen deposition would be a typical exponential function with distance from the cornfield.

The three-dimensional numerical model for simulating wind distribution over complex terrain can be used for simulating wind distribution around a cornfield and then the simulated wind distribution can be used for pollen diffusion model and statistical model as done by Kawashima et al. [2000]. Wind direction and wind speed play very important roles in the daily deposition of corn pollen, and daily air temperature change also affects pollen deposition, as described by Kawashima et al. [2001]. Results from our experiments can be applied for various plants to estimate both potential and integrated pollen deposition.

5. ACKNOWLEDGMENTS

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