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Development and validation of a quasi-Gaussian plume model for the transport of botanical spores

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ABSTRACT

Aerial dispersal of inoculum is the primary means of movement for many plant diseases. One of the challenges of modern decision support for plant health is to provide predictions of the influx of viable pathogen inoculum from sources outside a crop. Such prediction in a practical setting requires prediction tools that have modest computing and input requirements, yet provide sufficiently accurate predictions. In this paper a hybrid dispersion model is developed, combining Taylor's statistical theory of diffusion for horizontal dispersal with the eddy diffusion theory as implemented in the Lagrangian similarity diffusion model of [van Ulden, A.P., 1978. Simple estimates for vertical diffusion from sources near the ground. Atmos. Environ. 12, 2119–2124] and [Gryning, S.E., van Ulden, A.P., Larsen, S.E., 1983. Dispersion from a continuous ground-level source investigated by a K model. Q. J. Roy. Meteor. Soc. 109, 355–364]. The model is extended with a dry deposition method and an effective source strength. Model results are compared with experimental data for the transport of artificially released spores of *Lycopodium clavatum* above a potato canopy. The numerical results are in close agreement with the experimental data, which cover distances up to 100 m. Numerical predictions are compared to those produced by two alternative model versions and a previously published Gaussian plume model for the transport of spores above potato canopies. The potential for practical implementation of atmospheric dispersion models in plant disease decision support systems is discussed.

1. Introduction

The spread of pathogen inoculum to uninfected hosts is critical to the spatio-temporal development of plant disease epidemics. Improved computer simulation of spore transport in heterogeneous landscapes could lead to an increased understanding of the epidemiology of many aerially transmitted diseases. An increased understanding could in turn lead to new plant disease management strategies that rely more on information and less on insurance sprays. It is the long-term aim of our research to develop and use a multiple scale epidemiological model for potato late blight (causal agent *Phytophthora infestans*) to investigate (in a spatial context) operational and strategic issues pertaining to disease management. Dispersal modeling is of particular interest to potato late blight epidemiologists as empirical data on the survival of detached sporangia reveal that most spores are killed within 1 h on sunny days, but many survive for long periods on cloudy days (Mizubuti et al., 2000; Sunseri et al., 2002). Such information suggests a wide range of possible dispersal

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distances. However, as the dispersal of viable inoculum depends on a complex interplay of population biological, atmospheric and spore survival processes, it is difficult to simulate.

Atmospheric dispersion models from the meteorological sciences are available as potential tools to provide a physically realistic description of the effects of atmospheric conditions on spore transport and deposition. Their use in plant pathology is not new and a number of researchers have developed spore dispersion models and validated them against experimental data (e.g. Aylor, 1989; Aylor and Flesch, 2000; Aylor et al., 2001; de Jong et al., 2002; Spijkerboer et al., 2002; Aylor, 2005; Aylor and Boehm, 2006; Bourdôt et al., 2006). The majority of this work involved validation against experimental data for the escape of spores above the canopy or for dispersal over very short distances only. The scarcity of larger scale spore dispersal data sets means that validation of spore dispersion models over distances more relevant for between field spread of disease is relatively rare (e.g. Spijkerboer et al., 2002; Aylor and Boehm, 2006).

Gaussian plume models are immediately attractive as a simple, analytical means to describe the transport of spores; they are currently the most commonly used dispersion models to estimate the downwind impact of emission sources and are extensively tested around the world. They have modest computing and input requirements, and thus seem well suited to play a role as dispersal components in epidemiological simulation models. The Gaussian formula is derived under certain idealized conditions (steady state, horizontal homogeneity, constant wind speed, and constant eddy diffusivity) from the advection-diffusion equation for a passive scalar emitted from a point source (e.g. Pasquill and Smith, 1983; Seinfeld and Pandis, 1998). However, it was recognized as early as the 1960s by Gifford (1968), Pasquill (1974) and others that the conventional Gaussian formula is not always applicable for low level releases. Due to the presence of a dynamically and thermodynamically active surface, the lower atmosphere, or surface layer, is a region of strong wind shear and inhomogeneous turbulence. This means that constant wind speeds and eddy diffusivities are not realistic in the surface layer, which weakens the assumptions used to derive the Gaussian plume formula. This presents a problem for the application of Gaussian plume models in plant pathology (and other applications).

A number of researchers have investigated non-Gaussian diffusion models and compared their predictions with those of Gaussian models and experimental data (e.g. Elliot, 1961; Malhotra and Cermak, 1964; Huang and Drake, 1977; van Ulden, 1978; Nieuwstadt and van Ulden, 1978; Gryning et al., 1983; Hinrichson, 1986; Brown and Arya, 1993). Vertical distributions of tracer materials were observed to be of an exponential as opposed to a Gaussian form in the famous diffusion experiments of the Prairie Grass Project (Barad, 1958), the Green Glow Program (Barad and Fuquay, 1962) and the Hanford 67 diffusion experiments (Nikola, 1977). It is also not difficult to find examples in plant pathology that suggest the use of non-Gaussian diffusion models may be more appropriate for spore transport: McCartney (1990) measured exponential vertical profiles of *Pyrenopaziza brassicae* ascospores; Aylor and Qui (1996) and de Jong et al. (2002) observed vertical profiles of *Venturia inaequalis* spores that were exponential in shape; and Aylor et al. (2001) measured vertical profiles of *P. infestans* spores which were also of an exponential form.

A better description of low-level, vertical diffusion in a turbulent shear flow is given by allowing mean wind velocity and vertical eddy diffusivity to vary with height. Solution of the advection-diffusion equation with the gradient-transfer assumption requires specification of the spatial distribution of wind and eddy diffusivity, and realistic distributions of these variables generally require solution by a numerical method. However, such realistic solutions, due to their complexity and input requirements, are unsuitable as components in larger epidemic simulators. A more analytical approach is therefore necessary, where the intention is to parameterize eddy diffusivities as a function of the flow. Monin–Obukhov similarity relations provide the best means to describe the variation of eddy diffusivity with height and atmospheric stability, however, their use to represent wind speed and eddy diffusivity profiles prevents analytical solution of the advection-diffusion equation (Arya, 1999).

As early as the 1920s, the advection-diffusion equation for a ground level source was solved analytically with power laws inserted for the profiles of wind speed and eddy diffusivity. These plume dispersion models yield vertical concentration profiles of a general exponential form. van Ulden (1978) took such an approach, but then rewrote the power law solutions in terms of Monin–Obukhov similarity functions, giving a physically realistic description of the effect of stability on the structure of turbulence in the surface layer. By comparing numerical results with data from the Prairie Grass experiments (Barad, 1958), he showed that vertical concentration profiles at a distance of 100 m can be well described with an exponential function of height raised to a power, s. A follow-up study by Gryning et al. (1983) yielded analytical expressions for s for both stable and unstable conditions, giving numerical predictions that compared well with the Prairie Grass experiments at distances from 50 to 800 m. The Lagrangian similarity diffusion model of van Ulden (1978) and Gryning et al. (1983) currently still provides one of the best analytical descriptions of diffusion from a low-level source (see also Gryning et al., 1987).

In this paper we develop a hybrid, or quasi-Gaussian plume model for the dispersal of spores. The model combines Taylor's statistical theory of diffusion for horizontal dispersal with the Lagrangian similarity diffusion model of van Ulden (1978) and Gryning et al. (1983) for vertical dispersal. The potential of a non-Gaussian model for predicting and describing spore transport between fields is investigated through validation against the spore dispersal data of Spijkerboer et al. (2002). These data are particularly useful as dispersal is measured over distances up to 100 m from the source of spores. Numerical predictions are compared to two alternative model versions, and the Gaussian plume model of Spijkerboer et al. (2002) which was originally developed with these data. Table 1 provides a summary of symbol definitions and dimensions.

2. Field data used for model validation

The ability of the quasi-Gaussian and Gaussian plume models to predict spore plumes was tested by calculating expected