Agricultural and Forest Meteorology 211–212 (2015) 37–47

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Dispersion of particles released at the leading edge of a crop canopy

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ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form 26 February 2015
Accepted 20 April 2015
Available online 10 June 2015

Keywords:
Dispersion of particles
Canopy edge flow
Large-eddy simulation

ABSTRACT

A large-eddy simulation (LES) approach was used to investigate the flow characteristics at a canopy leading edge and their impact on the dispersion of particles released from point sources inside the canopy. Comparison of results from these LES simulations with those for a canopy that is infinite and uniform in both streamwise and spanwise directions reveals important insights about the adjustment lengths for mean flow, turbulent kinetic energy (TKE), and canopy-shear-layer vortices. Two critical locations were identified in the flow adjustment at the leading edge: (1) the location at which canopy-shear-layer vortices begin to develop and (2) the location at which the flow is fully developed. Simulations were conducted for particles released from continuous point sources at four streamwise locations downwind from the leading edge and three heights within the canopy. The four streamwise source locations corresponded to the canopy leading edge, the location at which canopy-shear-layer vortices began to develop, the transition region, and the fully developed region. The adjustment of flow near the leading edge has a profound impact on the dispersion of particles close to the source, which is where most particle escape from the canopy takes place. Particles released close to the canopy leading edge have much higher maximum escape fractions than particles released in the fully developed region. The adjustment length for particle escape is greater than that for the flow. Away from the source (approximately sixteen canopy heights for the present dense canopy), the geometries of the mean plume become similar for particles released from different regions. Within a few tens of canopy heights from the leading edge, the growth rates of converged mean plume height and depth are lower than those for the case of an infinite canopy.

1. Introduction

Many studies of turbulence and dispersion inside and above plant canopies are conducted for canopies that are infinite and uniform in both streamwise and spanwise directions (hereafter referred to as “infinite canopies”). The case of an infinite canopy represents conditions away from canopy edges where flow has adjusted to canopy characteristics (hereafter referred to as “fully developed region”, see Fig. 1). When wind blows over vegetated landscapes, the vegetation canopy acts as a displaced wall, inducing rough-wall boundary-layer eddies (*black eddies* in Fig. 1) above the displacement height ($\approx 3/4$ canopy height). Within the canopy, wakes are formed behind individual canopy elements. In addition, surface forces acting on canopy elements produce a net drag force on the air and dissipate the kinetic energy of the air. The presence of a drag force within the canopy and the absence of drag force above the canopy leads to an inflectional mean velocity profile, with the inflection point located near the canopy top. The shape of this canopy-shear-layer profile is similar to that in a free shear layer (mixing layer) formed between two uniform, parallel streams of different velocities (Raupach et al., 1996). The canopy and free shear layers are analogous in the inflectional mean wind profile, consequent flow instabilities, and in the second- and third-order turbulence statistics (Raupach et al., 1996). The non-linear interactions of boundary-layer eddies, canopy-shear-layer vortices (*red eddies* in Fig. 1), and wake eddies lead to an extremely complicated turbulence field within and just above the canopy, a region from the ground to approximately three canopy heights, known as the canopy roughness sublayer (Finnigan, 2000; Poggi et al., 2004). The dispersion of scalars and particles within the canopy roughness sublayer usually has a critical contribution from *near-field* dispersion, which is not a Fickian diffusive process and cannot be described by a diffusion equation (Raupach, 1989; Chamecki, 2013). Here *near-field* indicates that the time since particle release is short compared with the Lagrangian time scale (a measure of the coherence or persistence of turbulent motions), and therefore dispersion depends on the velocity histories of the tracer particles (Taylor, 1921; Raupach, 1983). In contrast, dispersion in the

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http://dx.doi.org/10.1016/j.agrformet.2015.04.012
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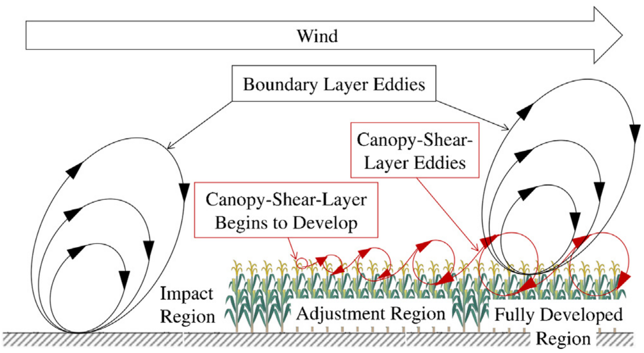

Fig. 1. Boundary-layer eddies (*black*) upwind from and above the canopy, and the development of canopy-shear-layer eddies (*red*) beginning a few canopy heights downwind from the leading edge. *Impact, adjustment, and fully developed regions* are labeled. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

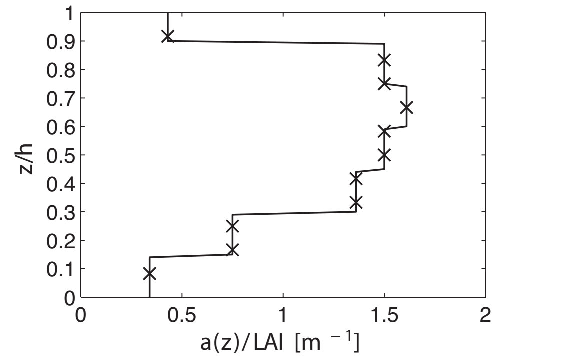

Fig. 2. Two-sided leaf area density, $a(z)$, normalized by one-sided leaf area index (LAI) for heights (z) normalized by canopy height (h), measured by Wilson et al. (1982) for a cornfield (*solid line*). Here LAI = 3.3 was measured by Gleicher et al. (2014) for the maize field of interest. *Crosses* indicate the values of $a(z)$ on the LES grid for horizontal velocity components.

far-field (for which the time since release is long compared with the Lagrangian time scale) no longer depends on the histories of the tracer particles, and thus becomes a diffusive process that can be described by a diffusion equation (Taylor, 1921; Raupach, 1983).

A recent large-eddy simulation (LES) study successfully reproduced both the turbulence statistics up to the third order and the three-dimensional (3-D) mean particle concentration field during a point-source *Lycopodium* spore release experiment conducted far from the edges of a large maize field (Pan et al., 2014a). However, a description of turbulence and dispersion within and above infinite canopies is insufficient for most environmental applications, because most landscapes are a patchwork of different vegetation types and land uses. In many regions, the fields are small compared to the flow adjustment length at the edge of the canopy, and therefore a large portion of the landscape is occupied by field edge. Understanding the transport processes at the canopy edge is therefore critical for interpreting flux measurements of sensible heat, water vapor, CO_2, and air pollutants (Lee, 2000), as well as estimating the dispersal of biogenic particles such as pollens (Di-Giovanni and Kevan, 1991) and spores (McCartney, 1994). In particular, measurements suggest that pathogenic fungal spores released at the canopy leading edge (transition from flat ground to a single vegetation type) tend to disperse farther than those released in the center of the field (McCartney, 1994). This finding implies that infection foci at the canopy leading edge are more likely to develop into disease epidemics than those in the fully developed region.

Turbulent flows downwind from canopy leading edges have been studied using field (Irvine et al., 1997; van Breugel et al., 1999; Nieveen et al., 2001) and wind tunnel (Judd et al., 1996; Morse et al., 2002) measurements, theoretical models (Belcher et al., 2003), and LES models (Yang et al., 2006a,b; Dupont and Brunet, 2008a,b, 2009). Belcher et al. (2003) suggested that the leading edge flow could be divided into five regions based on the characteristics of mean flow and downward momentum flux: (1) the *impact region* located upwind from the edge, (2) the *adjustment region* within the canopy where the flow is decelerated by canopy drag, (3) the *canopy interior region* where the canopy drag is balanced by downward momentum flux, (4) the *canopy shear layer* at the canopy top where coherent structures develop, and (5) the *roughness-change region* above the canopy where the internal boundary layer (IBL) develops (see Belcher et al., 2003, Fig. 3). An important parameter in their model is the canopy-drag length scale, L_c, representing the length scale over which the canopy dissipates the kinetic energy of the flow (Belcher et al., 2003, 2008). LES results of Dupont and Brunet (2009) suggest four stages in the development of coherent structures near the canopy leading edge: (1) *canopy-shear-layer instabilities* develop close to the leading edge due to drag discontinuity at the canopy top, (2) *transverse vortices* form once the canopy-shear-layer instabilities roll over, (3) *two counter-rotating streamwise vortices* appear as secondary instabilities destabilize these rollers, and (4) *complex 3-D coherent structures* develop from the streamwise vortices with spatially constant mean length and separation length scales. The authors used a length scale proportional to the depth of the IBL to characterize the distance occupied by coherent structures in each stage of development. Note that this length scale can also be related to the canopy-drag length scale, because stages develop closer to the leading edge with increasing canopy density (Dupont and Brunet, 2009). One would expect different patterns of particle dispersion for sources located in these regions of distinct flow characteristics.

The objective of this work is to use an LES model to further investigate the flow structure at the canopy leading edge and to explore its impact on the dispersion of particles released from points sources inside the canopy. The LES model is described in Section 2. The adjustment of the flow above and within the canopy is the focus of Section 3, with an emphasis on examining the adjustment lengths for mean flow, turbulent kinetic energy (TKE), and canopy-shear-layer coherent structures. The influence of source location on the dispersion of particles is investigated in Section 4, focusing on the geometry of the mean plume and the escape of particles from the canopy. Effects of mean vertical advection and canopy-shear-layer vortices on the growth of mean plume height and the ground deposition of particles are discussed in Section 5. Conclusions are presented in Section 6.

2. Numerical model

The LES model employed in this work was described in detail in Pan et al. (2014a,b). The model solved the 3-D conservation equations of fluid momentum and particle concentration, implying that a continuous concentration field was advected by a continuous velocity field. Coriolis force and buoyancy effects were not considered. The most important effect of the canopy on the airflow was to exert a drag force that dissipates the kinetic energy of the air. A distributed drag force ($\boldsymbol{f}_D$) was used to represent the surface forces exerted by canopy elements within the grid volume and was parameterized following the standard practice in LES studies,

$$\boldsymbol{f}_D = -C_D(a\mathbf{P})\cdot(|\tilde{\boldsymbol{u}}|\tilde{\boldsymbol{u}}). \quad (1)$$

Here $\tilde{\boldsymbol{u}}$ is the filtered velocity, $a\,\boldsymbol{P}$ is the two-sided leaf area density (a; Fig. 2) split into streamwise (x), spanwise (y), and vertical (z) directions using a diagonal second-order projection tensor ($\mathbf{P}$). The value of $\mathbf{P} = P_x\,\boldsymbol{e}_x\,\boldsymbol{e}_x + P_y\,\boldsymbol{e}_y\,\boldsymbol{e}_y + P_z\,\boldsymbol{e}_z\,\boldsymbol{e}_z$ ($P_x = P_y = 0.28$, $P_z = 0.44$)