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Long-distance edge effects in a pine forest with a deep and sparse trunk space: In situ and numerical experiments

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ABSTRACT

As forest edges are a major source of heterogeneity in fragmented landscapes, the atmospheric flow over forested areas is often under their influence. Understanding how far the upstream edge has an impact on the turbulent wind flow in a forest canopy is important, in particular for scalar flux measurement. In this study, edge and stand flows over a maritime pine forest characterized by a dense crown layer located above a deep and sparse trunk space are analysed in detail from in situ measurements and large-eddy simulations (LES). The LES model used here appears to simulate remarkably well most characteristics of the turbulent wind flow for this particular canopy structure. It is shown that the main characteristics of the edge flow in this case differ from those usually observed in forests with a more uniform vertical foliage distribution. The main differences are (i) the development of turbulence above the canopy occurring closer to the edge, (ii) the absence of a well-defined enhanced gust zone around the top of the canopy, (iii) the presence of a large secondary wind maximum within the trunk space, and (iv) the development of a positive momentum flux layer below the crown layer. Most of these differences are related to the presence of a substantial sub-canopy wind jet induced by the wind flow through the trunk space at the edge. The secondary velocity maximum induced by this wind jet differs from that observed in homogeneous stand conditions, where it seems to be related to the mesoscale pressure gradient. The wind jet appears to decrease very slowly with distance from the edge, so that edge effects are still significant at 9*h* from the edge (where *h* is the mean canopy height). The length of the adjustment region is shown to be greater than 10–15*h*, and to depend on the depth of the trunk space. In very fragmented forested areas with deep and sparse trunk space, within-canopy flow may always be under the influence of edges.

1. Introduction

Over the past few years assessing the carbon balance of terrestrial ecosystems has been the subject of many studies related to climate change, because of the role of carbon dioxide on the greenhouse effect. In order to address the current uncertainty on carbon exchange between the biosphere and the atmosphere, many tower sites have been set up all over the world within the FLUXNET international network (Baldocchi et al., 2001). However the eddy-covariance technique used to measure surface fluxes shows some limits in non-homogeneous surface conditions. At several sites, significant errors have been observed in measurements of nighttime and daytime turbulent fluxes due to advective transport generated by the presence of topography or canopy heterogeneities like clearings, roads, forest patches of various height, etc. (e.g. (Aubinet et al., 2003, 2005; Feigenwinter et al., 2004, 2008; Yi et al., 2008)). Such heterogeneities may indeed have significant impact on the atmospheric flow in the vicinity of vegetation. Forest edges in particular have been studied for this purpose (Chen et al., 1993; Cadenasso and Pickett, 2000). It has been shown that the location of a flux tower with respect to the edges has to be carefully considered because of potential risks of advection (Finnigan, 2008). Edge flow still needs to be better understood, one key issue being the distance required by the flow to adjust with the canopy.

Over the last decades, turbulent flow over forest edges has been studied from wind-tunnel (Chen et al., 1995; Raupach et al., 1987) and field (Raynor, 1971; Gash, 1986; Kruijt et al., 1995; Irvine et al., 1997; Flesch and Wilson, 1999; Nieveen et al., 2001) experiments (see Lee, 2000 for a brief review of studies on disturbed flow across forest edges). It has also been analysed from analytic models (Belcher et al., 2003) and numerical experiments (Li and Lin, 1990; Green, 1992; Liu et al., 1996; Foudhil et al., 2005; Yang et al., 2006b,a; Dupont and Brunet, 2008a,b, 2009). An edge flow exhibits several regions that have been described in these studies, mostly in the case of canopies with a relative uniform vertical foliage distribution (see, for example, Belcher et al., 2003; Dupont and Brunet, 2009).

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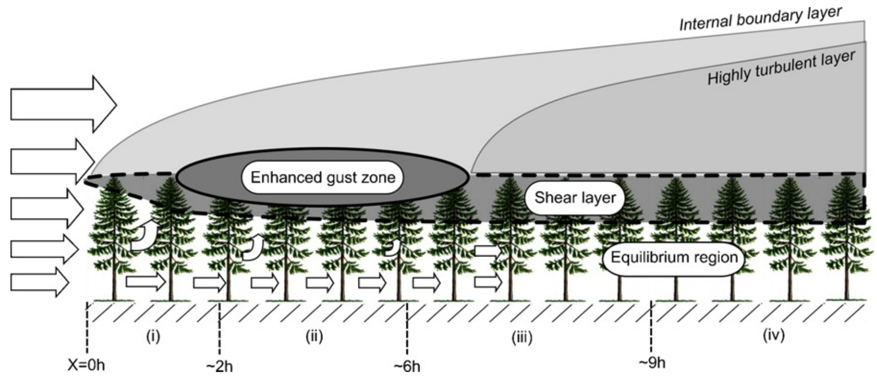

Fig. 1. Idealized representation of the main characteristics of edge flow over a canopy with an LAI of about 2 and a relatively uniform vertical foliage distribution. Figure adapted from Dupont and Brunet (2009).

Fig. 1 summarizes the main characteristics of edge flow. Slightly upwind from the edge, the flow starts to decelerate due to the pressure gradient induced by the presence of the canopy. A growing internal boundary layer develops above it. In the adjustment region, the streamwise wind flow decelerates within the canopy, inducing by continuity an upward motion from the canopy to the roughness layer above. Turbulence decreases within the canopy due to the presence of small wake eddies generated by plant elements, which enhances the rate of turbulence dissipation. It also decreases in the enhanced gust zone at canopy top, because of vertical advection from the canopy interior (Dupont and Brunet, 2008a). In this region the streamwise velocity skewness exhibits a maximum larger than 1.5, which indicates an asymmetric distribution of wind velocity around its mean value, and a high probability of sudden strong events (gusts). Further downstream a turbulent region develops above the canopy as a growing layer within the internal boundary layer. At around 8–10h (where h is the mean canopy height), the flow is adjusted with the canopy and the shear layer is well developed; it is characterized by the presence of coherent structures responsible for most of the momentum, mass and heat exchanges between the canopy and the atmosphere (Raupach et al., 1996).

The distance required by the flow to equilibrate with the canopy, referred to as the length of the adjustment region L_a, is usually estimated as about 8–10 h, a distance that decreases with increasing canopy density (Dupont and Brunet, 2008a). Recently Belcher et al. (2008) estimated this distance from an analytic treatment of a neutrally stratified flow as about $3L_c$, where L_c is the adjustment length scale for momentum, which only depends on canopy properties (canopy drag coefficient and leaf area density). This distance was corroborated by measurements over arrays of model trees, cubes and cylinders (Belcher et al., 2008). However this definition implies that the adjustment length scale only depends on bulk canopy properties and does not take account of the vertical distribution of foliage area.

Maritime pine forest canopies exhibit strong vertical heterogeneity: they usually have a deep and sparse trunk space and the crown layer is concentrated in the upper third, or less, of the whole canopy depth. In such a configuration Dupont and Brunet (2008a) showed with a large-eddy simulation model that the length of the adjustment region may be larger than in more uniform canopies (e.g., 15h or 6L_c). In parallel, apparent positive (i.e. upward) momentum fluxes have been repeatedly measured just below the crown layer at the maritime pine site of Le Bray, in Southwestern France (unpublished results). Careful inspection of measured time series and repeated intercomparison of the turbulence sensors had led us to the conclusion that the possibility for measurement errors was unlikely.

So the goal of the present study is to analyse in detail the edge flow dynamics in the case of a deep, sparse trunk space, as can be found in a maritime pine forest. It is based on the combination of measurements and large-eddy simulations. After a presentation of the field (Section 2) and numerical (Section 3) experiments, the main statistical wind characteristics are compared in stand and edge wind sectors (Section 4). In Section 5 specific features are discussed (the secondary wind maximum and the positive momentum flux observed within the trunk space), and the length of the adjustment region is evaluated in various canopy cases differing mainly by the depth of the trunk space. We finally conclude by summarizing the main characteristics of the edge flow in a maritime pine forest (Section 7).

2. Field experiment

2.1. Research site

The measurements used here were performed in the period 2006–2008 in a maritime pine forest (*Pinus pinaster* Ait.) at Le Bray site (44°43′ N, 0°46′ W), located in Les Landes region in Southwestern France. The forest plot was planted in 1970 in a regular array with 4 m spacing between adjacent rows and 3 m spacing between trees along each row. This site has been part of the Euroflux, Carboflux, CarboEurope and Fluxnet international networks. Long-term measurements of CO_2 net exchange and water vapour fluxes have been performed there from a 40 m high tower (e.g. Baldocchi et al., 2001; Berbigier et al., 2001; Lamaud et al., 2001; Misson et al., 2007; Jarosz et al., 2008). Short-term experiments have also been occasionally set up at this site, to study for instance the characteristics of wind flow dynamics and coherent eddy structures (e.g. Collineau and Brunet, 1993; Brunet and Irvine, 2000), or wind–tree interactions (e.g. Sellier et al., 2008).

The forest was mature at the time of the experiment, with a mean tree height h of approximately 22 m. Stand density was about 410 trees ha^{-1}, leaf area index (LAI) about 1.8, and the mean stem diameter at breast height about 0.33 m. The forest was characterized by a dense crown layer located between 13 m and 22 m, and a very sparse and open trunk space below 13 m. The mean vertical distribution of the frontal area density A_f is shown in Fig. 2b. It is estimated from probability functions of the leaf area density, deduced by combining branch level models and architectural measurements (Porté et al., 2000). The soil was covered with graminae approximately 0.7 m high with a LAI of about 1.5.

Until 2000 this site fulfilled remarkably well the homogeneity criteria required for the eddy covariance method: the ground surface was flat (slope less than 0.2° in all directions) and the site was surrounded by similar stands, with a fetch greater than 1 km in the prevailing wind directions. Following the December 1999 Lothar windstorm, clearcuts were made at about 200 m (9h) to the North-