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Large Eddy Simulation of Coherent Structures over Forest Canopy

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Abstract. This paper deals with the numerical simulation (using a LES approach) of the interaction between an atmospheric boundary layer (ABL) and a canopy, representing a forest cover. This problem was studied for a homogeneous configuration representing the situation encountered above a continuous forest cover, and a heterogeneous configuration representing the situation similar to an edge or a clearing in a forest. The numerical results, reproduced correctly all the main characteristics of this flow, as reported in the literature: the formation of a first generation of coherent structures aligned transversally from the wind flow direction, the reorganisation and the deformation of these vortex tubes to horse shoe structures. The results obtained, introducing a discontinuity in the canopy (reproducing a clearing or a fuel break in a forest), were compared with experimental data collected in a wind tunnel. The results confirmed the existence of a strong turbulence activity inside the canopy at a distance equal to 8 times the height of the canopy, referenced in the literature as an Enhance Gust Zone (EGZ) characterized by a local peak of the skewness factor.

1 Introduction

The studies concerning the interactions between turbulence and canopy can interest numerous environmental problems such as the evaluation of the heat and mass

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transfer between the atmospheric boundary layer (ABL) and a forest, the effects of wind gusts on trees plantations, the effects of wind on the behaviour of wild-fires. Compared to a standard boundary flow, the structure of the flow above a forest canopy presents more similarities with a mixing layer [1, 2]. The drag force induced by the elements constituting the canopy (foliage, branches, twigs) slows down the wind flow inside the vegetation layer. The resulting action of this force, induces a significant shear of the free wind flow above the canopy, in a similar manner than the situation observed in a mixing layer. For dense canopies, the flow inside the canopy is structured in two zones [5]:

- a wake zone located just near the ground, where the streamwise velocity profile is nearly uniform and mainly affected by the micro-wakes generated by the elements (foliage, branches) composing the vegetation
- an exchange zone, located at the upper layer of the canopy, dominated by strong shear effects and quick exchanges with the external flow

To observe the transition between a standard atmospheric boundary layer flow (ABL) and a mixing layer (ML) type flow, the drag force induced by the canopy must be larger than a threshold value. A critical parameter can be defined to express the ABL/ML transition, using the product between the average drag coefficient C_d , with the Leaf Area Index (LAI). The transition is observed when this physical parameter is larger than a critical value nearly equal to 0.1 ($C_d \times LAI > 0.1$) [4]. The shear layer induced by the presence of the canopy upon the wind flow promotes the development of a Kelvin-Helmholtz (KH) instability, characterized by the formation large scale three dimensional structures with a horse shoe shape [2, 3]. The development of such large scale structures, are responsible of the penetration of coherent gusts inside the canopy, inducing longitudinal wave motions across the vegetation called "Honami" [4].

Many authors highlighted that the wavelength of these coherent structure - Λ_X (streamwise direction), was correlated to the shear length scale L_S , defined as the ratio between the average streamwise velocity with the vertical shear rate ($L_S = dU/dz$) evaluated at the top of the canopy $z = H$ [6, 7].

In the present study, we demonstrated some characteristics stages of the coherent turbulent structures formation, using large eddy simulation (LES) carried out for continuous and discontinuous forest canopy.

2 Physical and Mathematical Model

Classically in a LES formulation, the equations of motion (momentum, continuity) governing the atmospheric flow inside and above the canopy were filtered to eliminate small scale perturbations [8]:

$$\begin{aligned} [!t] \frac{\partial}{\partial t} (\rho \langle u_i \rangle) + \frac{\partial}{\partial x_j} (\rho \langle u_i \rangle \langle u_j \rangle) = - \frac{\partial \langle p \rangle}{\partial x_i} + \mu_L \frac{\partial}{\partial x_j} \left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i} \right) + \\ \frac{\partial \tau_{ij}}{\partial x_j} + \rho a_L C_d (\langle u_i \rangle \langle u_j \rangle)^{1/2} \langle u_i \rangle, \quad \frac{\partial \langle u_j \rangle}{\partial x_j} = 0, \end{aligned} \quad (1)$$

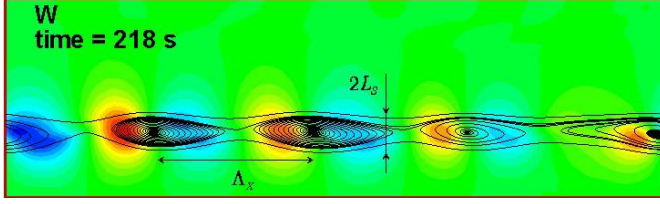


Fig. 1 Snapshot of the vertical velocity component w calculated above a continuous canopy (on the right)

where the brackets $\langle \rangle$, denote the filtered variables: u_i is the velocity component in the x_i -direction, p is the pressure, ρ is the air density, τ_{ij} is the subgrid-scale (SGS) flux of momentum. The final term on the right hand side of Eq. (1) represents the sink of momentum due to the presence of the vegetation. For this term, we introduced two parameters: the leaf area density a_L and the drag coefficient C_d . Because of the actions resulting from the micro-wakes induced by the elements constituting the vegetation (foliage, twigs), the effective drag coefficient measured in-situ inside a canopy, was smaller than the value which can be measured individually for one particle in a wind tunnel. This phenomena is known in the literature, as the shelter effect [1]. In agreement with experimental measurements, the average drag coefficient C_d was chosen to be constant and equal to 0.15.

As adopted classically by the ABL community, the SGS momentum flux in Eq. (1) is evaluated using the eddy viscosity concept calculated from the SGS kinetics energy k and a length scale $L = (\Delta x \Delta y \Delta z)^{1/3}$ (where Δx , Δy , Δz are the grid sizes in the three directions of space) [8, 9, 10]. The SGS kinetics energy is predicted solving the following transport equation [8]:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho \langle u_j \rangle k) = \frac{\partial}{\partial x_j} \left(\mu_T \left(\frac{\partial k}{\partial x_j} \right) \right) + \tau_{ij} \frac{\partial \langle u_i \rangle}{\partial x_j} - \rho C_\varepsilon \frac{k^{3/2}}{L} - 2a_L \rho C_d (\langle u_i \rangle \langle u_j \rangle)^{1/2} k. \quad (2)$$

For the dissipation term (proportional to $k^{2/3}$), we introduced two parameters: the constant model $C_\varepsilon = 0.93$ and one more time the SGS length scale L . The final term in Eq. (2) represents the sink for SGS kinetics energy due to the rapid dissipation of wake turbulence in the lee of elements constituting the vegetation layer (foliage, twigs, branches). The set of transport equations (1), (2) were solved using a implicit Finite Volumes method, using a QUICK third order scheme (with a flux limiting strategy) for the convective terms and a second order central difference scheme for the diffusive terms.

3 Results and Discussion

A first set of numerical simulations was performed for a continuous canopy. The vertical structure of the vegetation (especially the distribution of the leaf area

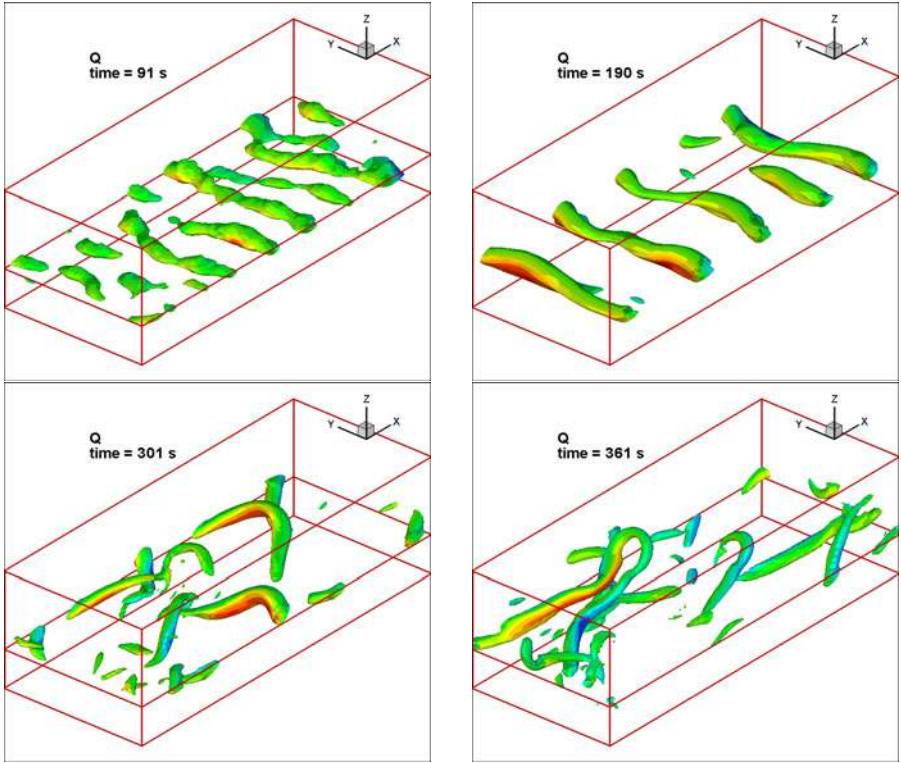


Fig. 2 Turbulent structures (Q -isosurfaces) above a homogeneous forest canopy computed at different times

density) was chosen to reproduce a pine forest (Jack pines), often encountered in boreal forest, for which a large number of experimental campaigns were already reported in the literature. This type of canopy is generally composed with two species Black Spruce (height $\sim 10m$) and Jack Pine (height $\sim 20m$), the Leaf Area Index (LAI) was here equal to 2. The dimensions of the computational domain were: $L_X = 200m$, $L_Y = 80m$ - horizontal directions parallel and perpendicular to the wind direction, $L_Z = 60m = 3H$ - vertical direction. The boundary conditions imposed at the limit of the domain were periodic at the vertical inlet and outlet faces and on the two lateral faces. At the top of the domain we imposed a streamwise velocity component equal to $3.8m/s$.

A snapshot of the distribution of the vertical component $\langle u_3 \rangle = w$ is shown in Figure 1. This result highlights clearly the formation of transverse coherent structures. The average streamlines allowed to extract the wavelength of these structures Λ_X , which was approximately equal to 8 times the shear length scale L_S , in good agreement with the previous results proposed by [6]. This first step for the organization of the flow, resulted from the development a KH instability, promoted by the shear of the wind flow at the interface between the top of the canopy and the free

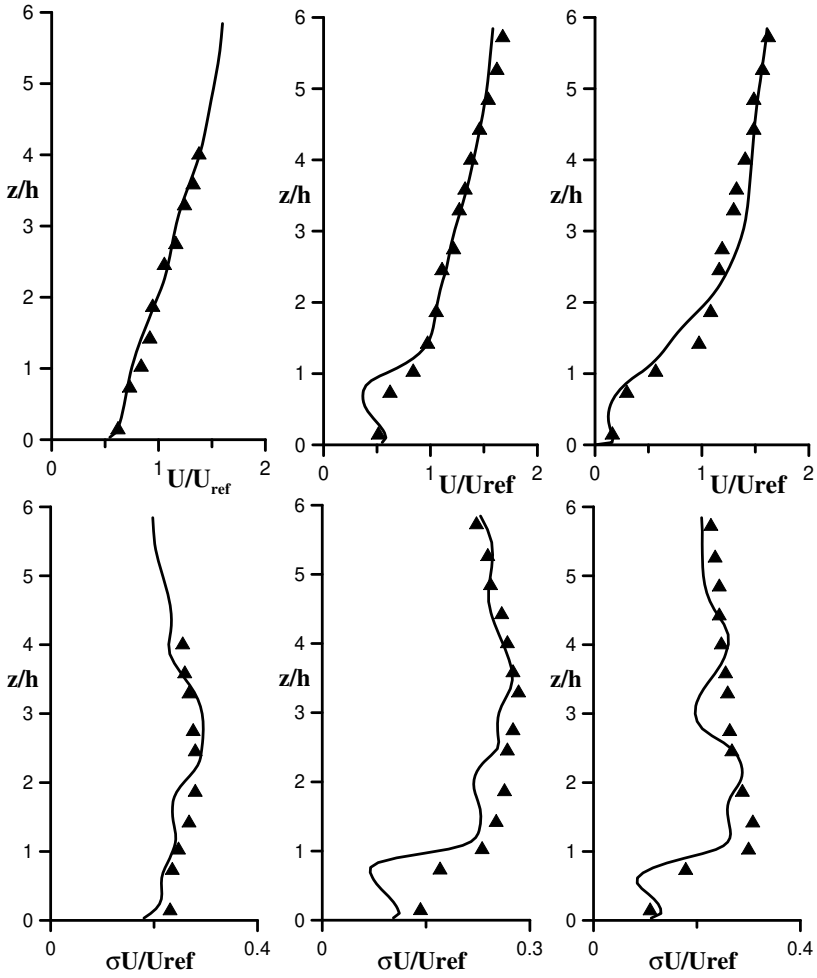


Fig. 3 Vertical profiles of streamwise wind velocity U and standard deviation σ_U at various distances downwind from the leading edge ($x/H = -8.5, 2.1, 10.6$), compared with experimental data [12]

zone located just above (see Figure 2, top on the left). The second step was marked by the clumping of these initial structures, into larger transverse rolls, connected by regions of highly sheared flow (see Figure 2, top on the right). The third step is the development of a secondary transverse instability, transforming the alignment of transverse rolls, into horseshoe shape structures (see Figure 2, bottom).

Then the configuration was extended to study the modifications induced by the creation of a discontinuity inside the forest cover. This particular configuration can represent the situation encountered at a forest edge or in a clearing. In this case the height of the canopy H was reduced to 7.5 m , the dimension of the clearing was

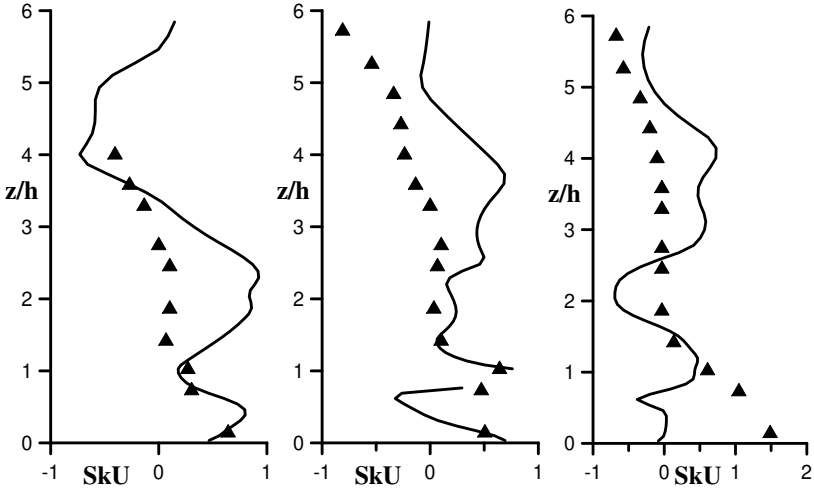


Fig. 4 Vertical profiles of streamwise velocity skewness Sk_U at various distances downwind from the leading edge ($x/H = -8.5, 2.1, 10.6$), compared with experimental data [12]

fixed to $21.3H$, the origin ($x = 0$) was chosen at the exit side of the clearing, in such a way that the point $x/H = -8.5$ was located inside the clearing, and the two other positions $x/H = 2.1$ and 10.6 were located in the region newly cover by the forest. The results shown in Figure 3 and 4, represent the distribution of average streamwise velocity U , the standard deviation σ_U and the skewness factor Sk_U , calculated for these three positions ($x/H = -8.5, 2.1, 10.6$), all the data were reduced using the canopy height H and a reference velocity U_{ref} evaluated approximatively at the middle of the clearing, $2H$ above the ground level.

As shown in Figure 3 and 4, the comparison theory/experience seems to be more satisfying for U , and σ_U , the agreement is less positive for Sk_U . For the profile crossing the canopy ($x/H = 2.1$ and 10.6) the effects of the drag force induced by the presence of the vegetation were correctly reproduced (in shape and intensity) for all these statistical moments:

- The modules of U and σ_U for the streamwise component of the velocity vector were significantly reduced inside the canopy. We noticed an inflection point for U at the top of the canopy ($z/H = 1$), favorising the development of a KH instability.
- We noticed the existence of a second local maximum on the velocity profile located near the clearing ($x/H = 2.1$), in the region located between the ground level and the crown based height (CBH), where the vegetation was less dense.

Even if the agreement with experimental data for the skewness factor Sk_U was less satisfactory (this high order moment, needs probably a smaller mesh size), the general tendency was correctly reproduced, i.e. positive values for the region located inside the canopy ($z/H \leq 1$), resulting from the incursion of gusts coming from the free flow above the canopy [13].

4 Conclusion

The interaction between an atmospheric boundary layer (ABL) and a forest canopy was simulated using a LES approach. The numerical results obtained above a continuous canopy confirmed that this flow presented numerous similarities with a mixing layer. The visualisation of large scale coherent structures, highlighted how the shear induced by the presence of the vegetation upon the free part of the flow, contributed to the organization of the flow. The numerical results were compared with experimental data obtained both for a homogeneous and an heterogeneous canopy.

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