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NUMERICAL SIMULATION OF TURBULENT FLOW IN A FORESTED PARK DAMAGED BY A WINDSTORM

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1. INTRODUCTION

The December 1999 Lothar windstorm that affected Western Europe caused extensive damages to French forests. The large spatial variability in the observed damages may be explained in a number of cases by the fragility of tree species or by local soil conditions. However, it also seems that high levels of fragmentation of the forest have induced very heterogeneous flow patterns that may have resulted in the formation of local regions of particularly high turbulence intensity.

In order to understand and explain the origin of the heterogeneity in the damages caused by the windstorm on tree stands, three-dimensional numerical simulations were performed in the particular case of a heterogeneous forested park in the city of Strasbourg (France), in which a few sections were devastated by the storm whereas other parts remained unaffected. For this purpose the atmospheric, dynamical flow equations are solved in neutral conditions within and above the tree canopy over the whole park using Aquilon, a CFD type model adapted to canopy flow (Foudhil et al., 2004). Turbulence is modelled statistically with a k-ε closure scheme. The flow equations in the canopy are modified to account for the drag forces and the production of turbulent kinetic energy by the vegetation. The model has been previously validated in 2D cases (continuous and discontinuous vegetation canopies) against wind-tunnel and *in-situ* measurements (Foudhil et al., 2004).

After a description of the park and its representation in the simulations, the levels of turbulence intensity simulated across the park are analysed.

2. DESCRIPTION OF THE SIMULATIONS

The park is spatially heterogeneous and displays a range of tree species (mostly deciduous trees) and a few buildings. The terrain around the park is flat, with a mixture of bare soil and small vegetation. The few forested areas existing in the surroundings of the park are considered in the simulations, as they may influence the dynamics of the flow inside the park. In 2003 the park was described in details by splitting it into a number of forested areas, with relatively homogeneous stand structures. Information on the botanical composition, the shape and the size of the trees were available for each of these forested areas. From this description and the use of aerial pictures, the morphological configuration of the park before the 1999 windstorm was deduced for the present study. In particular, the average canopy height and frontal area density were assessed for each forested area. The frontal area density A_f of the canopy is used in the calculation of the drag force induced by the vegetation. It is assumed that A_f is equivalent to the leaf area index and that A_f, as well as the drag coefficient C_d, are constant vertically. The latter assumption seems reasonable given the average architecture of the park trees, as well as the vertical resolution used here. For the sake of simplicity, the buildings are assimilated to very dense vegetation.

The weather data recorded at the airport of Strasbourg on the day of the storm show that the average wind velocity reached 98.2 km h^{-1} at 10 m above the ground, with gusts going up to 129.6 km h^{-1}. The average wind came from the South-West at the beginning of the storm and the West at the end of it. As the numerical simulations are stationary, the average conditions of the 1999 windstorm are used to simulate the average fields at the scale of the park.

The model equations are solved over a 1900 x 1200 x 350 m domain with a 20 m horizontal resolution and a 1.2 m vertical resolution within the canopy. The average characteristics of the park are deduced for each cell from the characteristics of each forested and built areas weighted by their respective surface density. Simulations are carried out by assuming that the incoming flow at the inlet boundaries is in equilibrium with the ground, characterized by a roughness length z_0 = 0.01 m. The mean velocity profile therefore follows a logarithmic law, with a friction velocity u_* set at 0.35 m s^{-1} and a West-South-West wind direction; the mean turbulent kinetic energy and its dissipation rate are deduced from the equilibrium relationships. The lower boundary conditions are given by wall functions at the ground; the upper ones, at the top of the computational domain, are provided by surface layer equations.

In order to limit computational time, the value of u_* used here is smaller than those prevailing during the windstorm. Previous simulations with larger u_* (not presented here) indeed showed that the spatial variability of turbulent kinetic energy is not sensitive to u_*. The magnitude of the energy in these turbulent areas can then be estimated by similarity.

3. RESULTS AND DISCUSSION

Figure 1a shows the canopy structure along a vertical section in the streamwise direction displayed

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in Figure 1c. It can be seen from Figure 1b, representing the normalized turbulent kinetic energy $E\,u_*^{-2}$ in this vertical section, that the flow is subject to a distorsion when it hits the park. This distorsion is characterized by a positive vertical velocity and a decrease in the horizontal velocity downwind of the park edge. Consequently, a strong wind shear is localized at the top of the park. A region of intense turbulence develops from $x/H \approx 16$ above the park, due to this shear. This region is then advected downwind of the park and the turbulence diffuses towards the ground.

A parallel between the park and a continuous canopy can be drawn. Similar patterns in the turbulent variables have been observed in two-dimensional continuous canopies (see, for example, Liu et al., 1996, and Morse et al., 2002). The turbulence production above the park is not effective from the leading edge of the park, as shown by our results but also by experiments reported in the literature. Morse et al. (2002) explain that this delay is due to the flow distorsion. Indeed, the turbulent development coincides with the decrease in the vertical velocity towards zero values (not shown here). The large turbulent intensity simulated at the leading edge of the park may be questionable. This production seems to be due to too large wake production by the vegetation at this level of the canopy. A deeper analysis of the origin and realism of these levels of turbulent kinetic energy needs to be performed.

Figure 1c represents the spatial variation in the normalised turbulent kinetic energy $E\,u_*^{-2}$ over a horizontal section at 37 m, *i.e.* above the park. At this height, the region of intense turbulence observed in the vertical section is visible at the scale of the whole park. The delay in the development of this region from the leading edge of the park varies spatially, inasmuch as the location of its initiation does not correspond to a mere translation of the park leading edge, but depends on the spatial heterogeneity of the canopy encountered by the flow. The turbulent region develops all the closer to the park leading edge as the canopy is continuous in the streamwise direction, because the wind shear at the top of the canopy is stronger there. Thus, in the North-West corner of the park, the turbulent region starts to develop at a distance of 6 H from the leading edge (where H = 29 m is the mean tree height) whereas in the centre of the park it starts at 17 H. At the latter location, the wind shear at the top of the park is broken by the successive gaps in the canopy. We may expect that intense wind gusts develop from this turbulent region and penetrate into the canopy.

The position of this region of strong turbulence above the park corresponds surprisingly well with that of the damaged areas of the park (see Figure 1c). It thus seems that the damaged areas are strongly correlated with the dynamics of the flow. An analysis of the ground conditions, tree rooting and tree health is currently being carried out to confirm or infirm these conclusions based on the dynamics of the flow as a possible cause for the observed damages.

4. REFERENCES

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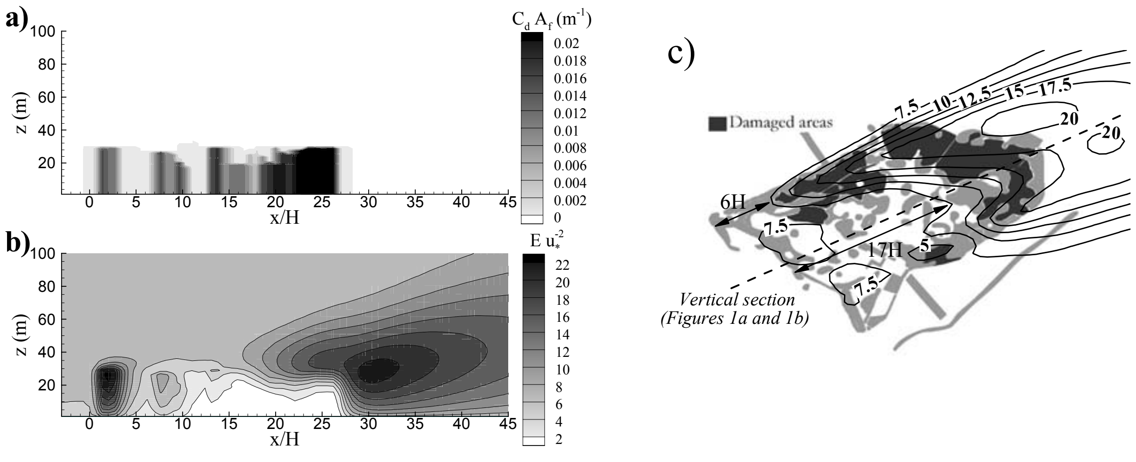

Figure 1. (a) Mean drag parameter (C_d is the drag coefficient and A_f the frontal area density) in a vertical section of the park (see Figure 1c), where H = 29 m is the mean tree height. (b) Normalized turbulent kinetic energy ($E\,u_*^{-2}$) simulated in the vertical section of the park. (c) Iso-contours of the normalized turbulent kinetic energy at 37 m above the ground. The dark areas represent the regions of the park severely damaged by the 1999 windstorm, and the grey zones correspond to the regions that remained unaffected.