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Effect of surface roughness on large-scale downburst-like outflows

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SUMMARY:
Downbursts are negatively buoyant descending winds coming from thunderstorm clouds that spread on the horizontal upon impinging the ground. Surface roughness is known to govern the characteristics of synoptic-scale atmospheric boundary layer (ABL) winds. This study assesses whether the same holds for downburst outflows and to which degree. The downburst winds are experimentally reproduced as a large-scale impinging jet at the WindEEE Dome, at Western University (Canada). Three different surfaces were tested and the equivalent full-scale roughness length is quantified through a best-match approach between experimentally produced ABL winds and ESDU profiles. The highest roughness produces an outflow vertical profile with maximum velocity reduced in magnitude and occurring at higher elevation with respect to the smaller-roughness cases.

Keywords: Downburst, Surface roughness, Wind tunnel.

1. INTRODUCTION

Surface roughness length z_0 plays a key role in the characterization of magnitude and structure of the mean velocity and turbulence profiles in boundary layer winds. There is still little literature assessing the quantitative contribution of surface roughness to the developed downburst outflow that forms upon the downdraft impingement on the surface (Fujita, 1985). Xu and Hangan (2008) and Mason et al. (2009) analyzed the dependency of the maximum slowly-varying mean radial velocity $\bar{V}_{\max}$ and its height of occurrence $z_{\max}$ with the surface roughness. They concordantly found that an increase of z_0 decreases the magnitude of $\bar{V}_{\max}$ and raises its elevation $z_{\max}$ above the surface. The offset of the two quantities with respect to the smooth surface tests increases along the radial direction of outflow convection, as turbulence has more time to influence the developing wall jet flow that radially diverges onto the surface. The diverging radial trend of $\bar{V}_{\max}$ and $z_{\max}$ continues until a balance is reached between inner layer, affected by the wall friction, and the sheared flow in the outer layer. The extent of such variations is strictly dependent to the Reynolds number, Re, as expected in case of rough wall boundary layer. Xu and Hangan (2008) observed that for Re > 1.0×10^6 the flow can be considered as “fully turbulent” and be representative of full-scale downburst winds. In this flow regime, the roughness term governs the equation and the detachment of $\bar{V}_{\max}$ and $z_{\max}$ from the smooth-surface reference case appears much more pronounced with respect to the laminar flow regime at low Re.

The impinging jet (IJ) experiments described in the current study were performed at the WindEEE Dome, which is currently the largest-scale wind simulator capable of reproducing extreme wind events, such as downburst winds, at “fully turbulent” regime.

2. EXPERIMENT SETUP

Figure 1 schematically shows the experimental setup top view. Three different surfaces were tested: (i) WindEEE Dome bare floor; (ii) Carpet; (iii) Artificial grass. Each surface was characterized with an equivalent full-scale roughness length z_0 that was assessed by running different ABL-like profiles inside the testing chamber and varying the length scale. A geometric scale of 1:200 was determined based on a qualitative matching of the mean velocity vertical profiles between physically reproduced and ESDU ABL profiles. The resulting equivalent roughness lengths were respectively z_0 = 0.007, 0.02 and 0.32 m. The downburst-like IJ was released from a nozzle of diameter D = 3.2 m located on the ceiling of the testing chamber. The nozzle-to-surface distance was H = 3.75 m. Two different intensities of IJs were used corresponding to centerline jet velocities W_{jet} at the nozzle outlet of 8.9 and 12.4 m s^{-1}. These are equivalent to $\text{Re} = W_{\text{jet}} D/\nu = 1.92 \times 10^6$ and 2.68×10^6, which allows to consider the flow in “fully turbulent” regime (Xu and Hangan, 2008).

A stiff mast with eleven Cobra probes was placed at 10 radial positions, r/D, in the range 0.2–2.0 with an increment of 0.2. The cobra probe heights above the WindEEE Dome floor were z = 0.040, 0.070, 0.100, 0.125, 0.150, 0.200, 0.300, 0.400, 0.500, 0.700 and 1.000 m.

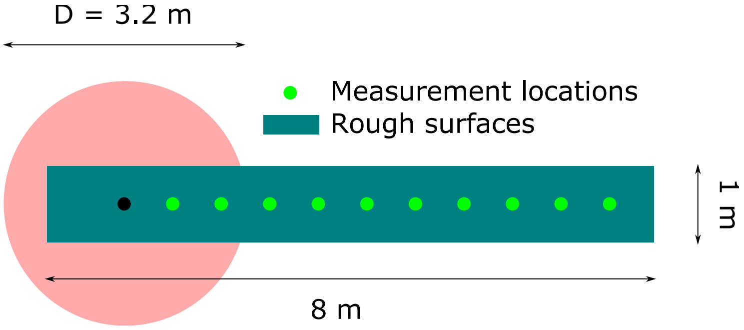

Figure 1. Experimental setup top view.

3. RESULTS

Figure 2 shows the vertical profiles of the slowly-varying mean horizontal velocity at the time of their maximum intensity. The dependency of $\bar{V}_{\max}$ and $z_{\max}$ with z_0 strongly corroborates the observations above. Also, the increasing offset of the two quantities with the radial position is validated. The surface with the highest roughness length z_0 = 0.32 m produces a much larger shear in the velocity vertical profile. However, no significant variations are observed between the two smaller-roughness cases, i.e., z_0 = 0.007 and 0.02 m.

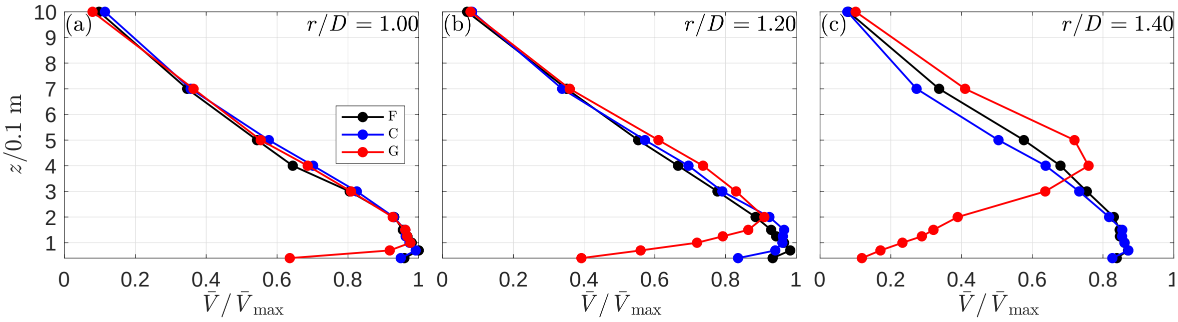

Figure 2. Slowly-varying mean wind speed $\overline{V}$ vertical profiles at the peak for *Re* = 2.68×10^6 and *r/D* = 1.0, 1.2, 1.4 (F – WindEEE bare floor, C – Carpet, G – Artificial grass). $\overline{V}$ is normalized by the maximum slowly-varying mean velocity among the three cases and three radial locations investigated.

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