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Adjustment of a turbulent boundary layer flow to idealized urban surfaces: A large-eddy simulation study

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Accurate prediction of atmospheric boundary layer (ABL) flow and its interaction with urban surfaces is critical for understanding the transport of momentum and scalars within and above cities. This, in turn, is essential for predicting the local climate and pollutant dispersion patterns in urban areas. Large-eddy simulation (LES) explicitly resolves the large-scale turbulent eddy motions and, therefore, can potentially provide improved understanding and prediction of flows inside and above urban canopies. This study focuses on the validation and the use of a recently-developed LES framework to simulate a turbulent boundary layer flow through idealized urban canopies represented by uniform arrays of cubes. The LES framework is first validated with wind tunnel experimental data. Good agreement between the simulation results and the experimental data are found in the vertical and spanwise profiles of mean velocities and velocity standard deviations at different streamwise locations. Next, the model is used to simulate ABL flows over surface transitions from a flat homogeneous terrain to aligned and staggered arrays of cubes with height h. For both configurations, five different frontal area densities (λ_f), equal to 0.028, 0.063, 0.111, 0.174 and 0.250, are considered. Within the arrays, the flow is found to adjust quickly and shows similar structure of the wake of the cubes after the second row. Above the arrays, an internal boundary layer (IBL) is identified. No significant difference in the depth of the IBL among different cases is observed. The drag exerted by the cubes on the flow (D_f) and the drag coefficients of the cubes (C_d) are calculated explicitly using the LES results. For the downstream cubes, D_f is found to increases with decreasing density for both configurations, and larger values of C_d are found for the cubes of staggered arrays than those of the aligned arrays with the same λ_f. At a downstream location where the flow immediately above the cube array is already adjusted to the surface, the spatially averaged velocity is found to have a logarithmic profile for all the cases. The values of the displacement height (d) are found to increase roughly from 0.65h to 0.9h as λ_f increases from 0.028 to 0.25 for both configurations. For the aerodynamic roughness (z_0), a maximum value at λ_f=0.11 is observed for both configurations. For all the cube densities tested, larger values of z_0 are obtained for the staggered arrays than for the aligned ones. The results of z_0 are discussed and compared with existing theoretical expressions proposed in the literature. The effective mixing length (l_m) within and above different cube arrays are also calculated using the LES results. A local maximum of l_m within the canopy is found in all the cases, with values ranging from $0.2h$ to $0.4h$. These patterns are different from those used in existing urban canopy models.