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Wind Field Characterization and Pollutant Transport in a Real Urban Canyon: A Large-Eddy Simulation Study in Bologna, Italy

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Urban street canyons are a critical part of the urban morphology, where building-induced flow structures and atmospheric turbulence jointly control pollutant dispersion and ventilation efficiency. While most existing studies rely on simplified, idealized canyon geometries, the complex spatial heterogeneity of real urban morphology remains largely underexplored. This study addresses this gap by numerically analysing wind dynamics and pollutant transport through high-fidelity Large-Eddy Simulation (LES) of a real neighborhood of the historical centre of the city of Bologna (Italy). This has been selected because a well-recognised hotspot for urban pollution and an archetypal case study of European cities, characterised by a dense, asymmetric urban configuration.

The LES is first validated against an experimental dataset obtained from a water channel experiment specifically designed to reproduce the same real city neighborhood. Also, numerical results are compared with RANS simulations previously carried out. The analysis pointed out the main processes driving the ventilation dynamics within the urban canopy layer: LES resolves the dominant turbulent structures governing momentum and scalar transport, including the primary canyon recirculation vortex and the rooftop shear layer originating at the upstream building. Turbulence generation is concentrated within this shear layer, which drives momentum exchange between the outer atmospheric flow and the canyon interior. Inside the canyon, turbulence remains persistently anisotropic, with streamwise and spanwise fluctuations dominating over vertical motions, while vertical mixing intensifies toward the taller downstream building. Velocity variaces distributions reveal spatially heterogeneous momentum transport, with deeper penetration of high-momentum fluid on the downstream side, a feature directly attributed to the building height asymmetry. Pollutant dispersion is governed by the interplay between recirculation-driven trapping and shear-layer-induced dispersion, producing non-uniform concentration fields with pronounced near-ground accumulation. Turbulent scalar flux analysis further uncovers counter-gradient transport upstream of the emission source and alternating ventilation and re-entrainment patterns. Comparison with RANS predictions highlights LES superiority in capturing vertical velocity and scalar transport, particularly within the rooftop shear layer.

These findings highlight that real urban geometry produces fundamentally three-dimensional, asymmetric flow and pollutant trapping mechanisms that idealized canyon models cannot

reproduce. Resolving unsteady turbulent structures via LES is essential, since mean-flow approaches miss the vertical mixing and counter-gradient transport that ultimately determine pedestrian-level air quality.