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Wind-driven rain exposure of pedestrians in urban environments

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SUMMARY

This study examines wind-driven rain exposure in a high-rise district in Geneva using windDrivenRainFoam, a code developed by the authors within the open-source platform OpenFOAM. Rain exposure refers to the amount of rain a pedestrian receives compared with fully open free field without obstructions. The results show that exposure is highest where down flow from tall buildings create corner streams and channeling flows that intensify pedestrian wetting, while low wind speed areas such as courtyards and building wakes offer more rain shelter. Because high-rise morphology strongly determines the wind conditions and how rain is transported and deposited at pedestrian level, wind-driven rain analysis is essential for designing effective rain shelters and improving outdoor comfort in dense urban environments.

Keywords: *Wind driven rain, rain exposure, high-rise buildings*

1. INTRODUCTION

Over the past decades, studies on wind-driven rain (WDR) have progressed from simple empirical observations to detailed numerical and CFD-based analyses. Building on Choi's early work (1993), Blocken and Carmeliet (2002, 2004, 2006) developed a quantitative WDR methodology using a Lagrangian approach for raindrop trajectories and steady-state 3D CFD simulations for wind flow around buildings. Catch ratio charts, relating WDR to horizontal rainfall, allow quantification of cumulative façade rain loads based on meteorological data. Their work also validated the model against experimental measurements and highlighted phenomena such as the wind-blocking effect, where high-rise buildings increase rain exposure at edges and corners while shielding lower windward surfaces. Coupling WDR models with heat and moisture transport models further enabled simulation of façade wetting and drying. Kubilay et al. (2013, 2014, 2015) advanced this approach with high-resolution field measurements and multiphase CFD simulations, accounting for building details and arrays of low- and mid-rise structures. Derome et al. (2017) reviewed key challenges in WDR modeling, identifying research priorities to improve accuracy and practical relevance. Recent studies show that urban environments reduce façade WDR loads due to wind shielding, while the methodology has been applied to assess heritage building durability under current and projected climate conditions. Kubilay and Allegrini (2018) also extended the method to evaluate pedestrian WDR exposure, which is further applied here in an urban high-rise context.

2. CASE STURY AND METHODOLOGY

The case study is located in the "La Praille–Acacias–Vernets" (PAV) district in Geneva, which is being redeveloped, with Place de l'Etoile planned as a central plaza surrounded by high-rise buildings. Figure 1a shows the height of the buildings in the domain of interest. Figure 1b presents the wind rose data under concurrent wind–rain conditions from 2019 to 2024, indicating that rainfall predominantly occurs with southwesterly winds, whereas rainfall is largely absent during northeasterly winds, the other primary wind direction.

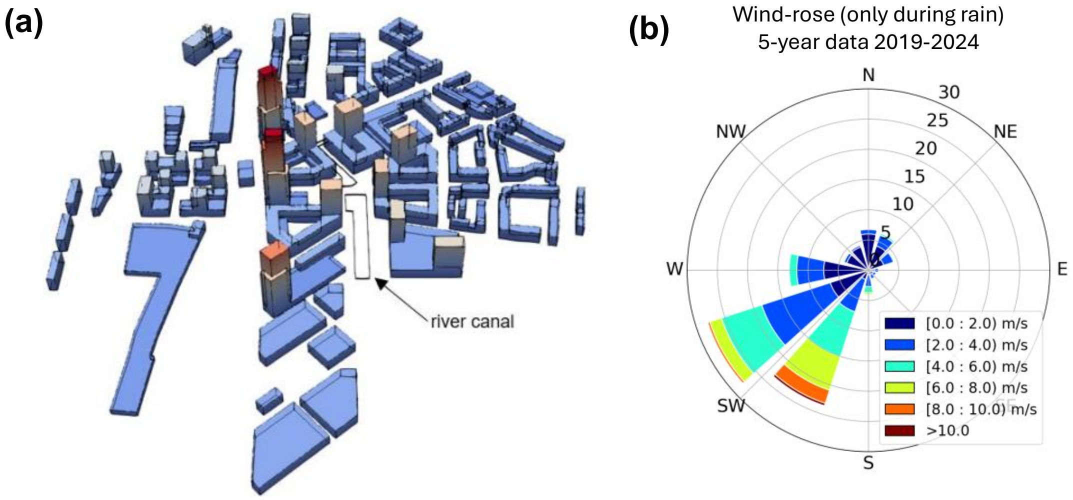

Figure 1. (a) Master plan with height of buildings around place l'Etoile with plaza in center and river canal. (b) Wind rose for periods with simultaneous wind and rain (2019–2024) derived from the MeteoSwiss station at Geneva Airport.

The windDrivenRainFoam model (2024), developed by the authors in OpenFOAM, is employed to assess wind-driven rain (WDR) on buildings and pedestrians. The model first computes steady wind fields using 3D incompressible RANS simulations with the realizable k–ε turbulence model (Shih et al., 1995), a widely validated approach for WDR studies (Blocken & Carmeliet, 2007). WDR is then simulated using an Eulerian Multiphase (EM) approach, where raindrops of different size classes are treated as continuous phases. The model accounts for gravity, aerodynamic drag (dependent on droplet size and relative velocity between air and rain), and turbulent dispersion (Kubilay et al., 2015). For each droplet size, a specific catch ratio is calculated, representing the fraction of horizontal rainfall intercepted by a surface, based on the velocity component perpendicular to the surface. Summing these contributions across all droplet sizes provides the overall catch ratio, which can then be used to generate charts of WDR intensity as a function of horizontal rainfall intensity and wind speed. These charts are combined with local meteorological data to estimate cumulative façade wetting over time.

For pedestrians, a global wetting ratio is computed similarly, using the magnitude of droplet velocity at pedestrian height to determine the fraction of rainfall that impacts the person (Kubilay & Allegrini, 2018). Comparing this wetting ratio at a specific location to that in free-field yields the rain exposure ratio, showing sheltering for values lower than one, and increased exposure for values higher than one.

3. RESULTS

Figure 2a presents the global catch-ratio pattern on the ground for a reference wind speed U=5 m/s at 10 m height and a horizontal rainfall intensity R_h=1mm/h, and wind directions from 120° to 210°. These horizontal surfaces generally exhibit catch-ratio values close to 1, meaning they receive rain amounts comparable to free-field conditions. However, local amplifications up to about 1.2 occur near high-rise buildings where downwash, corner streams, and channeling flows intensify raindrop impingement. In contrast, sheltered ground zones display reductions to 0.8 and lower.

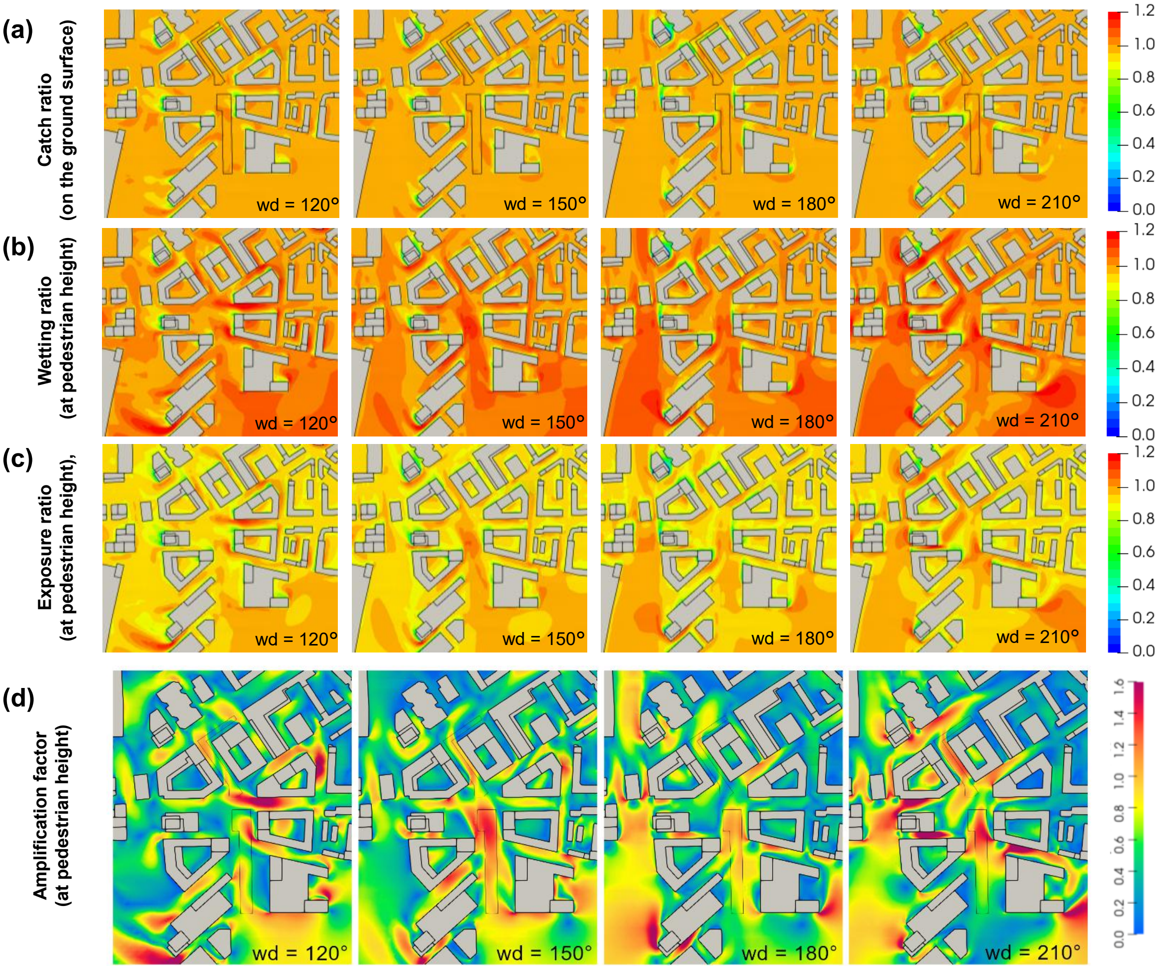

Figure 2. Results for for $U = 5\text{m/s}$, $R_h = 1\text{mm/h}$ and wind directions from 210°: (a) Global catch ratio on ground surfaces, (b) wetting ratio at pedestrian height, (c) rain exposure at pedestrian height, (d) amplification factor at 2 pedestrian height.

Figure 2b shows the maps of global wetting ratio on pedestrians for different wind directions including the dominant south-southwest direction. Compared to the catch ratio on horizontal surfaces, the wetting ratio, equivalent to the global catch ratio on pedestrians, shows higher values ranging mainly between 1 and 1.2. The higher values are caused by the higher velocities of rain droplets at pedestrian height compared to the normal velocity on horizontal surfaces.

Figure 2c shows maps of the rain-exposure ratio for different wind directions. The rain-exposure ratio quantifies the rain load experienced by a pedestrian relative to exposure in unobstructed free-field conditions. Exposure ratios mostly range from 0.6 to 1, with peaks around 1.2. Much of the domain exhibits values near 0.9, indicating that the buildings only shield to a limited values. These slightly lower values arise because urban wind speeds are reduced relative to the free field. Higher exposure, at times reaching 1.2, appears near windward façades of tall buildings, where downflow, corner streams and channeling flow enhance droplet transport. Lower ratios occur in building wakes, where shielding reduces pedestrian wetting.

A clear spatial correspondence exists between wind amplification patterns (Figure 2d) and rain-exposure fields, where the amplification factor is defined as the ratio of wind speed in the presence of buildings to that in an empty domain. It is clear that locations with the highest wind amplification facors also show the strongest rain exposure.

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