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Street-Level Sensing for Assessing Urban Microclimate (UMC) and Urban Heat Island (UHI) Effects on Air Quality

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Abstract: During the intense heatwaves of late summer 2024, Washington, D.C.'s urban landscape revealed the powerful influence of urban morphology on microclimates and air quality. This study investigates the impact of building height-to-width (H/W) ratios on the urban heat island (UHI) effect, using a combination of field measurements and Computational Fluid Dynamics (CFD) simulations to understand the dynamics. Street-level data collected from late August to November 2024 across three sites in Washington, D.C., indicate that high H/W ratios (1.5–2.0) increased temperatures by approximately 2–3 °C and reduced wind speeds to around 0.8 m/s. These conditions led to elevated pollutant concentrations, with ozone (O₃) ranging from 1.8 to 7.3 ppb, nitrogen dioxide (NO₂) from 0.3 to 0.5 ppm, and carbon monoxide (CO) remaining relatively constant at approximately 2.1 ppm. PM_{2.5} concentrations fluctuated between 2.8 and 0.4 µg/m³. Meanwhile, lower H/W ratios (less than 1.5) demonstrated better air circulation and lower pollution levels. The CFD simulations are in agreement with the experimental data, yielding an RMSE of 0.75 for temperature, demonstrating its utility for forecasting UHI effects under varying urban layouts. These results demonstrate the potential of Computational Fluid Dynamics in not only modeling but also predicting UHI dynamics.

Keywords: urban heat island (UHI); urban microclimate (UMC); urban morphology; air quality; temperature distribution; wind speed; computational fluid dynamics (CFD); ENVI-met; mobile monitoring; sensor nodes



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1. Introduction

The Urban Heat Island (UHI) phenomenon occurs when urban areas exhibit higher temperatures than their rural surroundings, with temperature differences ranging from 1 °C to 7 °C [1,2]. This phenomenon arises from a combination of factors, including the absorption and retention of heat by urban infrastructure, anthropogenic heat release, and reduced vegetative cover [3,4].

Urban microclimates, shaped by localized climatic conditions, exacerbate UHI effects such as heat retention, reduced nighttime cooling, and pollutant buildup in street canyons [5]. Furthermore, the interaction between UHI and air quality has significant health implications. The elevated temperatures caused by UHI accelerate chemical reactions in the atmosphere, leading to increased concentrations of pollutants such as tropospheric ozone and fine particulate matter. These pollutants contribute to respiratory diseases, cardiovascular diseases, and heat stress, particularly in vulnerable populations [6,7]. In addition,

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