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Unsteady urban buoyant flows and climate-dependent heat mitigation by trees

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SUMMARY

Urban climate and thermal comfort are shaped by airflow, heat transport, and vegetation within street canyons, where wind forcing and buoyancy create highly unsteady dynamics. This study combines high-resolution PIV/LIF experiments and LES simulations to investigate unsteady buoyant flows in simplified two-dimensional street canyons, alongside physical modelling of tree-induced microclimatic effects across arid, continental, and tropical climates. Results demonstrate that thermal plumes drive unsteady flow structures with frequencies increasing with thermal forcing. Trees consistently provide local cooling through shading and transpiration, but nonlocal downwind effects transition from heat stress mitigation in arid climates to amplification in tropical climates. These findings advance mechanistic understanding of canyon ventilation dynamics and provide critical guidance for climate-specific urban design strategies.

Keywords: *Urban buoyant flow, LES, heat mitigation, trees*

1. INTRODUCTION

Urban heat stress arises from complex interactions between temperature, humidity, airflow, radiation, urban morphology and trees. Understanding these interactions requires investigating two interconnected phenomena: unsteady buoyant flows driving ventilation within street canyons, and climate-dependent effectiveness of vegetation-based heat mitigation strategies.

Traditional urban climate studies emphasize time-averaged flow profiles, yet the fluctuating nature of velocity and heat flux remains insufficiently explored. Street canyons exposed to solar radiation generate highly unsteady flows where thermal plumes and vortical structures interact dynamically, but relationships between thermal forcing, buoyant flow structures, and canyon geometry remain poorly understood.

Recent research has generated conflicting evidence regarding vegetation as a heat mitigation strategy, with some studies suggesting humidity from transpiration intensifies heat stress while others demonstrate substantial cooling. Trees modify thermal comfort through shade provision, transpiration cooling with moisture addition, and airflow alteration, but the relative importance of these mechanisms varies across different climates from arid to tropical.

This study addresses both knowledge gaps through complementary approaches: simultaneous PIV/LIF measurements and high-resolution LES to examine unsteady buoyant canyon flows, combined with systematic high-resolution physical modeling of tree-induced microclimatic effects across diverse climates, establishing mechanistic understanding of canyon-scale ventilation dynamics and climate-dependent vegetation impacts. and validation of numerical models therefore require comprehensive measurement datasets.

2. UNSTEADY BUOYANT FLOW DYNAMICS IN STREET CANYONS

High-resolution particle image velocimetry (PIV) and laser-induced fluorescence (LIF) measurements were conducted simultaneously in a water tunnel to capture instantaneous velocity and temperature fields within simplified two-dimensional street canyons, complemented by large-eddy simulations (LES) (Figure 1a). Comparison between experiments and simulations at representative surface temperatures demonstrates good agreement (Figure 1b), successfully capturing flow structures and thermal forcing influences on velocity and temperature distributions. Analysis of flow and thermal fields at canyon openings revealed that the majority of heated fluid exits through the central roof region, while corners, particularly near the leeward wall, exhibit distinct behaviors influenced by canyon geometry. Roof-level velocity profiles display saddle-shaped distributions, while temperature profiles show dual peaks reflecting corner-induced features. Ventilation quantification through inflow and outflow rates demonstrated mass conservation across canyon openings, with only minor discrepancies attributable to numerical resolution. Heat flux analysis indicated that higher surface temperatures enhance net heat removal through the roof opening; however, this increased removal does not offset overall canyon air warming. Despite stronger upward flux, air temperature within the canyon remains higher at elevated heating levels, indicating that enhanced buoyancy-driven ventilation cannot compensate for intensified surface heating.

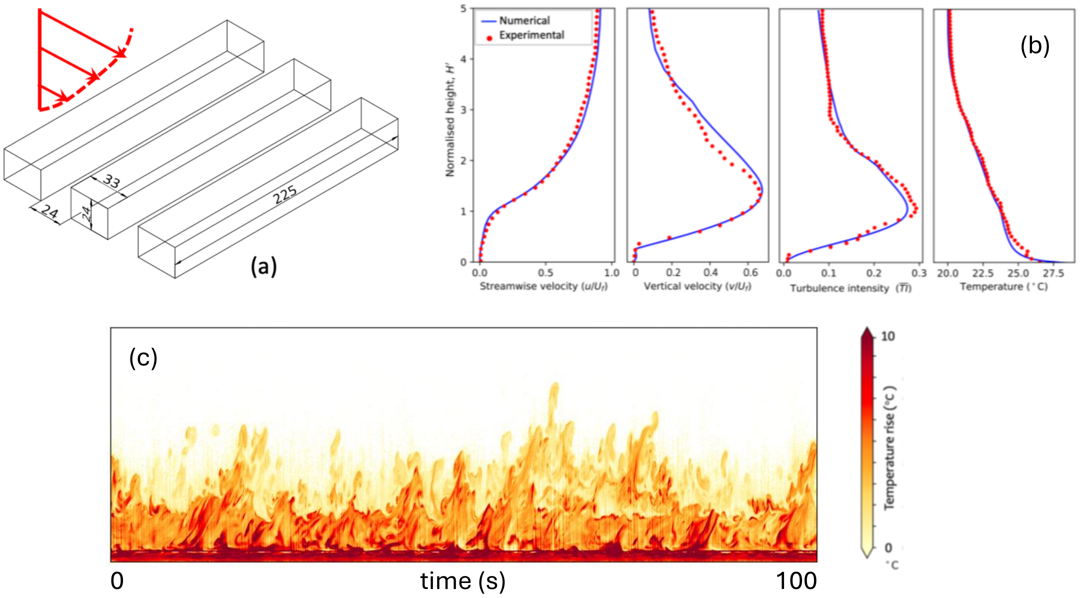

Figure 1. (a) Sketch of the 2D simplified street canyon model studied in this paper. (b) Comparison of normalized streamwise velocity, normalized vertical velocity, and temperature distribution along the centerline of the second canyon (c) Temporospatial plots of experimental centerline temperature rise at surface temperature of 45 °C (R=3.3) for a recording period of 100 s.

Fluctuating centerline temperature signals, observed experimentally and reproduced numerically, exhibited flame-like plume structures highlighting thermal updraft generation from heated canyon surfaces (Figure 1c). These plumes represent the primary mechanism driving flow unsteadiness and vertical heat transport, with characteristics strongly dependent on thermal forcing intensity. Frequency-domain analysis of roof heat flux provided insight into spectral characteristics of unsteady buoyant flows. At low Richardson numbers, buoyant flow displayed clear periodic structure with a single dominant frequency. With increasing thermal forcing and Richardson number, this dominant frequency shifted upward, reflecting accelerated plume generation and ejection cycles. Simultaneously, small-scale fluctuations emerged in power spectral density, indicating more complex unsteady behavior with multiple interacting temporal scales. This behavior suggests gradual transition from quasi-periodic, mechanically-dominated flows to more chaotic, thermally-dominated regimes. However, the present work does not yet establish fully quantitative relations between thermal forcing intensity, characteristic frequencies, and distinct flow regime boundaries. Canyon geometry influence on unsteady dynamics requires further systematic investigation.

3. CLIMATE-DEPENDENT TREE EFFECTS ON URBAN HEAT STRESS

To systematically evaluate climate dependence of tree-induced microclimatic effects, high-resolution physical modeling is conducted across three representative urban settings: arid, continental, and tropical climates using urbanMicroclimateFoam (Carmeliet and Derome 2024, Kubilay et al. 2018, 2020, urbanMicroclimateFoam 2024). These categories span the gradient of background wetness and vapor pressure deficit that constrains transpiration potential from trees and determines relative importance of different tree cooling mechanisms.

The simulations isolated local effects, occurring directly beneath and immediately adjacent to tree canopies, from nonlocal downwind effects propagating through advective transport of air masses with modified temperature and humidity. Universal Thermal Climate Index (UTCI) serves as the heat stress metric, integrating combined influences of air temperature, humidity, wind speed, and radiation.

Trees modify thermal comfort through three mechanisms: shade provision blocking incoming solar radiation; transpiration providing evaporative cooling while adding moisture to the air; and airflow alteration modifying convective heat and moisture transport. Analysis of the combined air temperature and relative humidity changes on UTCI revealed that impact of transpiration cooling on thermal comfort decreases progressively from arid to wet climates, approaching zero in tropical conditions where near-saturated ambient air limits evaporation. This produces relatively consistent local cooling across climate zones, primarily driven by shading.

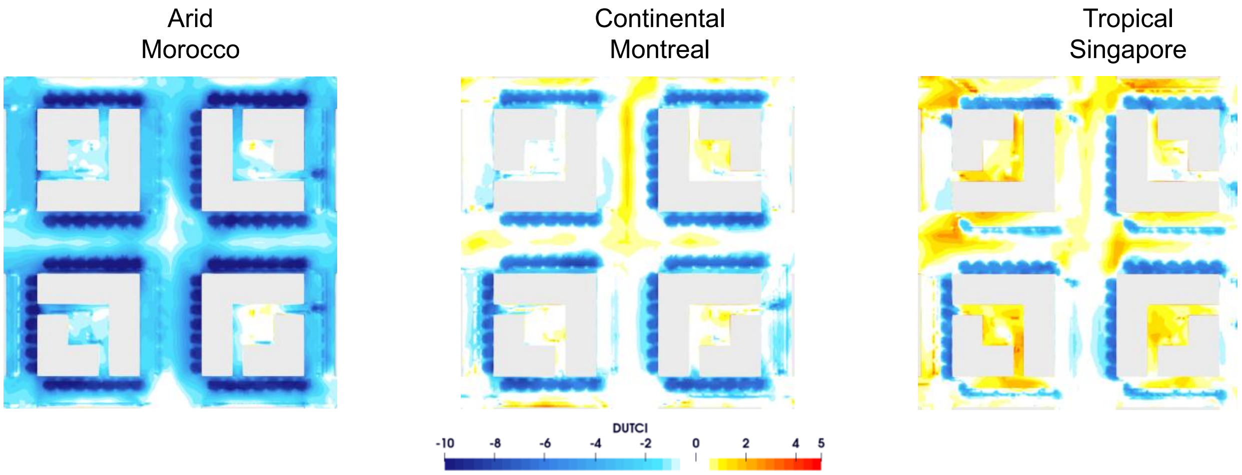

Figure 2. Example of the direct local cooling effect (dark blue), nonlocal cooling effect (cyan) and nonlocal heating (yellow to red) effect of trees in three different climates. Figure shows the difference in UTCI of the case with and without trees at 3 pm with a southerly wind with a velocity of 0.5 m/s.

However, nonlocal effects show striking climate-dependent reversal: transpiring trees reduce heat exposure in surrounding areas within arid climates, where substantial transpiration cooling persists downwind, but amplify heat exposure in neighboring areas within tropical climates, where limited cooling is overwhelmed by elevated humidity and reduced wind speeds advected downstream.

In arid climates, soil moisture limitation and stomatal closure rapidly suppress transpiration under drought. Unirrigated trees show only local heat exposure reduction due to residual shading, while becoming nonlocal heat sources due to warm, dry air advected downwind when transpiration ceases.

Effective heat mitigation requires climate-specific, neighborhood-scale planning accounting for both local and nonlocal effects. In arid climates, irrigation should be prioritized to maintain transpiration cooling, though water resource constraints must be considered. In tropical climates, tree placement should maximize local shading while minimizing downwind impacts through strategic spacing.

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urbanMicroclimateFoam - An open-source solver for coupled physical processes modeling urban microclimate based on OpenFOAM [WWW Document], 2024. URL https://github.com/OpenFOAM-BuildingPhysics/urbanMicroclimateFoam