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Realistic solar heating in urban areas: Air exchange and street-canyon ventilation

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A B S T R A C T

Numerical fluid flow and heat transfer simulations of a three-dimensional idealized urban environment are performed to investigate the effect of realistic non-uniform thermal forcing that is caused by solar insolation and inter-building shadowing. Simulations at different times of day are performed using Large Eddy Simulation (LES) and mean flow and turbulence statistics are investigated as determinants for urban canyon ventilation. The differential surface heating of the building canyon is parameterized using sets of horizontal and vertical Richardson numbers indicating atmospheric instability and solar tilt with respect to the wind direction, respectively. Roof heating, in combination with building walls and ground heating, is shown to be important in the strength and location of the canyon vortex. For example, in case of weak vertical stratification (Ri_v) and high horizontal temperature gradient opposing the wind direction above the canyon (Ri_h), the combination of roof heating and ground heating decreases the strength of the canyon vortex. The distribution of local convective heat transfer coefficients (CHTC) on building facets are analyzed. Throughout the day, the windward walls exhibit larger CHTCs and leeward heating enhances CHTC from the roof and windward walls. Additionally, the wall heating in the cross-stream canyon (north-south in our case) enhances the air exchange rate from the canyon, especially when the leeward wall is heated.

1. Introduction

The world is currently experiencing the largest wave of urbanization in history. According to the 2011 World Urbanization Prospects [1], more than 78% of the population in developed countries already lives in urban areas and the fraction is expected to increase worldwide. As urbanization progresses, microclimate modifications are aggravated in various ways [2–4] and Urban Heat Island effects become more prevalent [5]. The progressive replacement of natural surfaces by impervious materials and buildings modifies regional morphology and land cover. The urban radiation balance is altered by the reflection and obstruction of solar radiation as well as the reduction of thermal radiation losses due to small sky view factors [5]. Building roughness provides a momentum sink and causes wind sheltering within street canyons. The contrast between the urban and undisturbed climates is further enhanced by the input of anthropogenic heat, moisture and pollutants into the atmosphere by human activities [6]. Therefore, it is essential that we develop more sophisticated and comprehensive methods of urban thermal and flow analysis in order to investigate the combined effect of various urban climate processes.

Thermal forcing plays an important role in determining flow patterns and turbulent transport in built environments [7,8]. Various surface controls that affect the dynamic thermal and flow field behavior are widely documented in the literature (through numerical modeling or wind tunnel experiments) and are mostly categorized in 4 major factors: 1) building canyon geometry and configuration [9–12], 2) surface thermal properties [13–15], 3) ambient wind speed and direction [15,16], and 4) distribution and strength of surface heating with respect to the ambient wind [17–22]. When the building facades are heated by solar radiation during the day, buoyancy enhances turbulence [23], and the combination of buoyancy and inertial forces governs the heat and mass removal from the street canyon. For example, when the windward wall is warmer than the air, the upward buoyancy flux opposes the downward mechanical advection in the building canyon, and the flow structure in the building cavity adjusts to these counteracting effects. It is essential to also recognize the three-dimensional (3D)

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Nomenclature

Abbreviations

ACH	Air Exchange Rate
AR	Building Aspect Ratio, AR = H/W
DES	Detached Eddy Simulation
DS	Dynamic Smagorinsky-Lilly (model)
LES	Large Eddy Simulation
RANS	Reynolds-Averaged Navier–Stokes (equations)
TMY	Typical Meteorological Year
WALE	Wall-Adapting Local Eddy Viscosity (model)
WMLES	Algebraic Wall-Modeled LES (model)

Greek symbols

α	Surface albedo
ε	Surface emissivity
σ	Stephan–Boltzmann constant
τ_{ij}	Subgrid-scale stress
u_τ	Shear/friction velocity

Roman symbols

A_p	Plan area of roughness elements
A_T	Total surface area of roughness elements
C_p	Effective heat capacity of the ground
F_{gr-w}	View Factor from ground to wall
H	Building height
h	Convective Heat Transfer Coefficient (CHTC), $h = \frac{Q_h}{(T-T_{ref})}$
k	Effective thermal conductivity of the ground
L	Net longwave radiation flux
L_{inc}	Incident longwave radiation
Nu	Nusselt Number $Nu = \frac{hH}{k}$
Q_c	Conduction heat flux
Q_h	Sensible heat flux
Ri	Number
S	Shortwave radiation
S_{ij}	Strain-Rate tensor
T_a	Inlet air temperature
T_g	Ground surface temperature
T_H	Fluid air temperature at roof level
T_L,T_W	Leeward and windward wall temperature, respectively
T_{sky}	Sky radiation temperature
U_b	Average bulk wind velocity at inlet
W	Building spacing

Operators

$<Q>$	Spatial average
$\overline{Q}$	Time average
$\widehat{Q}$	Filtered quantity
Q^+	Dimensionless

nature of the urban canopy, including the interaction between buildings under non-idealized conditions [24]. For example, variation of solar position and insolation throughout the day result in 3D heterogeneous distribution of thermal forcing on urban facets. Non-uniform, 3D surface heating is not commonly considered in the literature. Since the solar irradiance field is not realistic the flow field within and above the canopy is also not expected to represent real conditions. To address this shortcoming, non-uniform thermal forcing and its 3D effect on urban flow field will be investigated.

Convective heat transfer coefficients (CHTCs) at exterior building surfaces determine turbulent heat fluxes and therefore affect building thermal loads and energy demands, canopy air exchange and pollutant dispersion. Empirical CHTC correlations for external urban surfaces have been evaluated using field measurements [25–30] and wind tunnel experiments [18], [22,31]. However, due to wind direction variability and complex canopy roughness especially in field experiments, the flow field and therefore the CHTC are very sensitive to the boundary conditions and inconsistencies between measurement campaigns were found [32–34]. Wall resolving Computational Fluid Dynamics (CFD) avoids the need to model Convective Heat Transfer Coefficients at external building surfaces [35–38]. However, the computational cost for simulations at realistic Reynolds numbers and over the diurnal cycle is too large. Consequently, simplified correlations are used to calculate or impose the value of CHTC. This results in large discrepancies among some of the widely used building simulation tools as reported by Refs. [39] and [40]. The latter suggests 20%–40% difference in energy demands with different choice of Convective Heat Transfer Coefficient. Furthermore, non-uniform and dynamic surface heating and associated changes in the flow field motivate the investigation of spatio-temporal distributions of CHTCs.

The air removal, or the capacity of the street canyon to "ventilate" itself, has a critical role on air quality, city breathability [41] and therefore quality of life of urban dwellers. Urban airflow and pollutant transport has received significant attention and several parameters have been introduced to quantify the ventilation performance. Liu et al. [42,43] considered the roof-level fluctuating vertical velocity as the sole responsible mechanism for air removal and pollutant dilution in the 2D street canyon. The Air Exchange Rate (ACH) was introduced by Liu et al. [44] to represent the volumetric air per unit time that is exchanged from the street canyon to the surrounding atmosphere. ACH was applied to compare the ventilation efficiency of street canyons [45–48]. The differential heating of building surfaces can also influence the exchange of air and pollutants [8]. Yet, numerical investigations on the effect of buoyancy on canyon ventilation have been relatively rare [20,46,49] and focused on idealized uniform surface heating scenarios. It is expected that non-uniform heating, significantly affects the air exchange rate.

In this paper, numerical fluid flow and heat transfer simulations of a three-dimensional (3D) urban environment are performed using the finite volume solver ANSYS/FLUENT 14.5. CFD simulation of urban microclimate is shown to be a powerful tool that can accurately model the urban thermal environment, as well as providing the possibility for comparative analysis [50]. Several studies demonstrated the importance of including shortwave and longwave radiation on accurately predicting the urban thermal environment and UHI effects in real urban configurations [50–53], however detailed analysis on the effect of thermal forcing on the local (street-scale) flow field is scarce. In this study an idealized compact low-rise geometry is used for generality [54], and the focus is on the detailed study of the determinants of urban thermal and flow environments. Accordingly, the main objective is to analyze the impact of non-uniform thermal forcing caused by varying incidence angles of direct beam shortwave radiation and shading effects between buildings on mean flow, turbulence statistics, temperatures, and canyon ventilation. Our model also extends previous urban analysis of CHTCs through a dynamic