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Editorial

Challenge for Multi-Scale Coupling Simulations of Wind and Heat Environment within Urban Canopy

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The urban canopy layer is defined as the atmospheric zone spanning from the ground surface to the rooftop level of urban buildings. It constitutes the most densely inhabited urban space with intensive human activities, as well as highly complex surface energy balance and material exchange processes. From a macroscopic perspective, densely distributed high-rise building clusters act as prominent aerodynamic resistance elements. Through strong frictional drag, these structures dissipate a substantial proportion of the mean kinetic energy of ambient airflow, leading to a considerable reduction in wind speed within the urban canopy [1]. The suppressed wind field weakens internal air ventilation and heat transfer efficiency, which further exacerbates the urban heat island effect. At the neighborhood-scale urban area, the heterogeneous configuration of building clusters induces distinct mechanical turbulence in near-surface airflow. Flow separation, vortex shedding, air recirculation, and wind shear jointly shape local flow fields that exhibit strong anisotropy, significant intermittency, and non-stationary features [2]. Accordingly, the urban canopy airflow is characterized by a coexistence of suppressed bulk ventilation and intense local flow pulsations. Such unstable flow regimes not only impair pedestrian comfort and walking stability while elevating gust wind risks, but also impose potential safety hazards on urban infrastructure systems.

Furthermore, building spatial layouts fundamentally govern urban airflow pathways. In deep, narrow street canyons, airflow is substantially blocked by flanking buildings, facilitating the formation of enclosed recirculation zones. This phenomenon causes prominent accumulation of vehicle emissions, atmospheric dust, and anthropogenic waste heat at pedestrian breathing heights [3], which drastically degrades urban air quality. The deteriorated microclimate significantly reduces outdoor spatial comfort, inhibits residents' outdoor travel willingness, and ultimately weakens the neighborhood's social interactive functions and commercial vitality [4]. Therefore, an in-depth exploration of microclimatic mechanisms within the urban canopy layer not only provides fundamental and theoretical support for revealing urban climate formation laws, but also serves as an essential prerequisite for public health protection, scientific urban planning, and the realization of sustainable urban development [5].

Mesoscale meteorological fields serve as the dynamic driver modulating microphysical atmospheric processes within the urban canopy layer. Multi-scale numerical simulation and assessment technologies for urban atmospheric environments centered on the urban canopy layer can not only quantitatively reconstruct historical meteorological and environmental records, but also predict the spatial distribution and temporal evolution of urban atmospheric environments in the future, yielding refined environmental information covering research scales from macro to micro and from coarse to fine resolutions. The characterization and parameterization of physical processes within the urban canopy layer constitute the core factors determining numerical simulation accuracy. Refined, high-resolution simulation of urban atmospheric environments has become an urgent research demand. High-precision numerical simulation of urban atmospheric environments enables the analysis of microscale

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physical processes, the identification of three-dimensional pollutant dynamics, and the quantification of urban heat island effects, among other applications [6].

Regular atmospheric observation and mesoscale meteorological forecasting models face some limitations in fine resolution. The Weather Research and Forecasting (WRF) model, which characterizes thermal and dynamic effects of urban underlying surfaces together with urban canopy parameterization schemes, has evolved into a standard tool for simulating wind, thermal and precipitation processes within the urban boundary layer [7,8]. Nevertheless, constrained by inherent model applicability, the typical horizontal resolution of WRF for urban domains stands at 1 km, accompanied by sparse vertical grid discretization near the ground. This restricts its capacity to resolve complex physical processes inside the urban canopy layer and impairs the overall accuracy of WRF urban atmospheric simulations [9]. Equipped with a comprehensive data assimilation subsystem (WRF-DA, WRF Data Assimilation), the WRF model integrates numerical forecast outputs with ground observational datasets to iteratively adjust initial and boundary conditions in real time. This ensures physical consistency of simulation results across temporal and spatial dimensions, and supplies accurate time-varying meteorological forcing data for downstream fine-scale modeling [10].

For atmospheric environment simulations at neighborhood scale (e.g., urban blocks) or microscale (e.g., street canyons), mesoscale WRF simulations or field observations are often used to provide parameters as initial and boundary conditions, so as to conduct high-resolution Computational Fluid Dynamics (CFD) numerical simulations at neighborhood scale or microscale. Representative CFD software packages include PALM (Parallelized Large-Eddy Simulation (LES) Model), ENVI-met (Reynolds-Averaged Navier-Stokes (RANS) method), ANSYS Fluent and OpenFOAM. CFD numerical simulations generally achieve meter-level spatial resolution, which renders them irreplaceable for scenarios requiring detailed characterization of geometric boundary effects [11].

CFD numerical simulations can acquire three-dimensional flow field data at arbitrary locations within the computational domain, enabling exploration of refined flow features such as vortex structures, flow separation and corner flows in confined complex spaces including street canyons and building surroundings. It has become a efficient tool for revealing the physical mechanisms of urban microclimates and evaluating the effectiveness of urban planning schemes [12]. For instance, the PALM-4U (PALM for Urban applications) framework tailored to urban scenarios integrates a suite of urban-oriented modules, namely building surface models, urban surface energy balance modules, vegetation canopy models, and extended functions associated with air quality and thermal comfort [13]. Within the PALM-4U framework, buildings are embedded into the computational domain as three-dimensional geometries and serve as impermeable solid boundaries that directly participate in flow and energy exchange processes. Notably, like most CFD simulation software, although the explicit wall modeling of buildings adopted by PALM exhibits the advantage in spatial resolution, it generates an enormous mesh grids or nodes. This renders PALM suitable only for high-precision local-scale research or typical scenario analysis [14,15], rather than simulations covering large scale domains or long scale time horizons.

Besides, the mesoscale WRF model leverages data assimilation algorithms within its dynamic core to continuously fuse direct and indirect observational or simulated data from disparate sources and variable resolutions that are spatially and temporally scattered. The model trajectory is automatically adjusted to enhance the estimation accuracy of dynamic model states and boost the predictive performance of mesoscale WRF simulations [10]. Conceivably, high-precision urban atmospheric parameters derived from CFD simulations can also be incorporated via data assimilation to refine mesoscale modeling. Nevertheless, constrained by the small coverage of CFD computational domains, no prior research has attempted to integrate CFD outputs into WRF data assimilation workflows. In practice, current CFD scenario simulations driven by meteorological fields output from mesoscale WRF adopt a one-way small-scale coupling strategy. Accordingly, there is an urgent demand to develop novel urban-scale LES approaches that balance computational efficiency and spatial resolution. By feeding LES results into mesoscale models through data assimilation, a dual-coupled WRF-LES simulation framework for urban atmospheric environments can be constructed to improve the forecasting capacity of mesoscale WRF for urban atmospheric conditions. In the following, three key issues will be discussed about the approach of dual-coupled WRF-LES simulation framework.

Issue 1, Developing urban-scale LES methods as regards innovative characterization of building physical effects to break limitations of explicit solid flow boundary representation. As mentioned above, conventional CFD simulations are restricted to small or microscale domains due to explicit geometric modeling of buildings, which yields massive mesh grids to resolve building drag and resistance effects. Expanding CFD simulation coverage to urban scales necessitates innovative modeling frameworks to parameterize building physical impacts. Taking a different perspective, the air movement within urban canopy can be regarded as the airflow passing through urban space as a porous medium, no longer the atmospheric flow along the solid wall

surfaces of buildings, thus building drag and resistance effects are instead of an urban porous media model (PMM) of drag source [6,16]. The PMM together with Local Climate Zones (LCZs) was preliminarily proposed to construct an LCZ-PMM LES simulation framework for urban-scale modeling [17]. The wind field in urban canopy layers of Xi'an, China was simulated with a grid spacing of 120 m horizontally and 1–3 m vertically. Urban LCZ datasets are sourced from the World Urban Database and Access Portal Tools (WUDAPT) database (www.wudapt.org). The PMM exploits the structural similarity between porous media and urban building clusters with vegetation: complex discrete building geometries are simplified into a unified porous medium framework, and the aerodynamic effects of building clusters with vegetation are parameterized as an equivalent drag field. This eliminates the need for explicit geometric modeling of intricate building layouts, drastically cutting mesh requirements while retaining computational accuracy. Particularly, the porous media formulations for building clusters and vegetation layers can be unified to comprehensively account for their respective drag effects as well as thermal and moisture atmospheric feedbacks.

Issue 2, High-precision parameterization of drag and thermal source terms in the urban canopy porous media model. The LCZ-PMM urban-scale LES framework is essentially a quasi-three-dimensional porous media drag-source modeling approach. Moreover, LCZ classification scheme from WUDAPT only achieves an accuracy of 65%, failing to precisely capture fine urban morphological information and requiring higher-fidelity urban geospatial datasets for calibration [18]. The digital twin (DT) technology originates from the "mirror spatial information model" concept proposed by Professor Michael Grieves at the University of Michigan [19], and has matured into a pivotal technology enabling dynamic bidirectional interaction between physical entities and virtual digital models. Within urban science, DT technology establishes fully corresponding virtual replicas of physical cities, delivering a novel technical paradigm for smart city development [20,21]. Driven by rapid advances in big data and geographic information technologies, digital mapping of physical cities enables full extraction of urban spatial structures, supporting the construction of a Digital Twin-based Porous Media Model (DT-PMM) with integrated drag and thermal source terms. This model elevates the fidelity of urban canopy porous media parameterization and enables high-precision multi-physics coupled simulations of wind, heat and moisture distributions within the urban canopy layer [22].

Issue 3, Grid matching strategies and data assimilation schemes of dual physical parameter exchange between WRF and LES grids for WRF–LES dual coupling simulation method. The one-way coupling CFD simulations driven by WRF meteorological outputs employ static pre-defined initial and boundary conditions. For the proposed urban-scale WRF-LES dual coupling framework, two core subproblems must be addressed: (1) methodologies for configuring LES initial and boundary conditions dynamically forced by real-time WRF meteorological outputs; (2) data assimilation algorithms to feed high-resolution LES simulation outputs back into the WRF mesoscale model. The fundamental solution relies on nested, rationally matched dual grid systems for WRF and LES, alongside well-designed transition layers at the boundaries of urban-scale LES computational domains to guarantee mass flux conservation.

In summary, present CFD simulations operate as a one-way coupled downscaling scheme driven by meteorological outputs from the mesoscale WRF model for neighborhood-scale analysis. As a foundational tool for small and microscale atmospheric research, CFD excels at resolving intricate fine flow details. However, its applicability is hindered by prohibitive computational overhead and rigid boundary constraints, making it incapable of independently solving cross-scale forecasting problems spanning regional background meteorology down to neighborhood microclimates. Additionally, the mesoscale WRF meteorological model dynamically adjusts its trajectory via embedded data assimilation algorithms to refine state estimation and enhance forecast reliability.

In response, this study simplifies urban building clusters and their spatial layouts into a porous media framework, and proposes a DT-PMM drag-thermal source model paired with urban-scale LES simulation. DT technology delivers precise quantification of urban canopy physical parameters to improve LES output fidelity. Further dual coupling with the mesoscale WRF meteorological model resolves the limitation that standalone CFD simulations rely on externally prescribed dynamic mesoscale boundary conditions, while supplying high-resolution fine-scale data assimilation constraints for WRF dynamic forecasting.

Integrated with the DT porous media drag-thermal source model, a urban-scale LES simulation platform based on the open-source OpenFOAM software, and then a WRF-LES dual coupling simulation framework for urban atmospheric environments are developed. This methodology is expected to deliver a new-generation numerical simulation tool for high-accuracy modeling of urban wind, heat and moisture fields, and provide theoretical and technical support for scientific urban planning, urban heat island mitigation, and air pollution abatement.

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Conflicts of Interest

The authors declare no conflicts of interest.

Use of AI and AI-Assisted Technologies

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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