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Topography integration to wind downscaling

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ABSTRACT

In building energy simulations, an urban context is assessed for its impact on local wind conditions. This process, known as wind downscaling, generally considers terrain that is characterized by the obstructions such as buildings and trees. However, topography, the shape of a land, is hardly considered for its combined impact with terrain. Wind downscaling is particularly challenging in large urban areas for the required high computational costs, while the existing models are still in their infancy. This paper developed a method to integrate the topography effect in existing terrain-driven wind downscaling. To facilitate its utility in early design stages, sampling and interpolation approach were adopted for computational efficiency. Samples were generated for urban contexts, considering topography with slopes and terrain with buildings. These samples were geometrically modeled and assessed for outdoor wind speed in virtual wind tunnel tests with CFD simulations. The assessment results were analyzed and stored in a database, which was used to interpolate for a new condition. The proposed method was demonstrated for its reasonable accuracy and high computational efficiency by comparing the interpolation result with CFD simulation for an actual site.

1. Introduction

Urban areas have unique climatic behaviors in comparison to open fields, mainly due to buildings, roads, and anthropogenic heat that together modify the heat balance of regional climate [1]. The urban heat island effect, one of the main characteristics of urban climate, helps to generate detrimental smog and to cause outdoor thermal discomfort [2]. The cooling demand is higher for buildings in urban areas than in rural areas [3]. Hence, it is critical to access urban contexts for their influence on local climate for creating high-performance buildings and healthier urban conditions. Yet, the assessments of urban contexts are often over-simplified or outright ignored, especially at early design stages. It is particularly challenging to assess the wind due to its chaotic nature yet important for the heat balance of a microclimate [4,5]. Accurate assessment of wind may also help to design safer and more comfortable outdoor environments for pedestrians [6] while reducing deteriorations of building envelope and structural loads [7]. Difficulties arise mainly from the model developments in their infancy, high computational costs for a large territorial scope, and inherent complexities in terrain characteristics, especially for the dense urban area [8].

Prior to urban contexts, the base weather information is related to the challenges of climatic assessments. For building scale studies "Typical Meteorological Year (TMY)" is the dataset for regional climate. It contains a collection of 8760 h of weather data for a location, being produced by the National Renewable Energy Laboratory [9]. A TMY's weather data is generally measured and recorded away from an urban area, for which it easily loses its relevance. To resolve this discrepancy, a technique "climate downscaling" (often called "localization") is commonly used to take account of influential variables to relate regional climate data for a smaller territorial scope. For wind downscaling, elevation changes and land use types are the typical variables of considerations [10]. In building scale studies, terrains are characterized by buildings and trees, becoming an important variable for their influences in built environments. However, topographies and their combined effects with terrains are generally ignored in wind downscaling [11], regardless of their important role in airflow and heat prediction, often being more influential than terrains [12,13].

Three types of existing models are generally available for wind downscaling. The first type is urban atmospheric models, maintaining that a climate in a lower atmospheric layer within an urban

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area behaves distinctly from the upper counterpart, creating urban boundary layer [14]. This hypothesis called "Canyon" has been developed and validated for urban-scale studies. Depending on the physical characteristics of urban contexts, the vertical interaction of atmosphere is the main focus, which however was identified as a source of uncertainties for horizontal airflow [15]. This model has been widely accepted in building scale and wind engineering studies. The second type is outdoor nodal models, which extrapolate the use of indoor nodal model [16]. Outdoor nodal models have received attentions for its appropriateness in first-cut assessments in early design stages with its computational lightness and acceptable accuracy [17]. However, topographic effects on the wind would be hardly assessed due to the simple airflow calculation that was originally developed for indoor spaces. The third type is detailed airflow models, generally represented by Computational Fluid Dynamics (CFD). CFD enables calculating heat and mass transfer by solving their governing mathematical equations with a finite set of control volumes. CFD has been increasingly accepted in built environment analyses [18–20]. Its credibility has been improved that virtual wind tunnel tests with CFD have started replacing physical experiments [21]. More importantly, the interaction of airflow with a surface can be calculated for topographic effects and turbulences, one of the main advantages over two other model types. However, high computational resources [22] are required and its complexity necessitates domain experts [23], which together limit its use in early design stages.

To respond the identified issue in wind downscaling and challenges its existing models, the paper presents a methodological model to assess the combined effect of topography and terrain on outdoor wind environment, by integrating the capacities of CFD, especially for the interaction of airflow with a surface. The main challenge is to minimize the associated computational costs in CFD simulations while considering a large territorial scope of urban areas and a large number of weather data records in a TMY dataset. Hence, the proposed model aims to approximate solutions by adopting sampling and interpolation approach, commonly found in engineering and scientific experiments for acceptable accuracy with significant computational savings [24]. For sampling, a set of existing urban contexts is generated and assessed for their impact on downscaling by virtual wind tunnel tests with CFD simulation. For interpolation, the test result is stored in a database that can be used to approximate a solution for a new urban context. This approach would enable model users to incorporate the desired capacities of CFD without having to deal with the associated limitations.

2. Methods

The proposed method was composed with three major steps as in Fig. 1. The first major step was sampling of existing urban contexts, which were geometrically modeled with terrain and topography. For terrain, the samples were generated with buildings and streets, depending on the size and density of buildings in a region. The terrain definitions were adopted from the widely-used urban atmospheric model, listing four different types (See Appendix), hence the proposed method could be readily integrated into external building scale models such as EnergyPlus [25] and to other engineering applications [26]. For topography, slopes were added, positively or negatively, to the samples with the terrain. The second major step was airflow assessments. The generated samples were assessed for their impact on downscaling in virtual wind tunnel tests, by using CFD simulations. A regional wind speed from a TMY dataset was fed to the inlet plane and local wind speeds were observed at the outlet plane for downscaling effectiveness. This step included a pre-process to consider the area between a meteorological station and the area of interest by using an existing model, which created the vertical profile of wind speeds with the roughness of terrains. The third major step was a downscaling correlation for data portability and for easy integration with external models. The physical properties of the urban context samples were correlated with their downscaling effectiveness. The developed correlation was used to interpolate for a new urban context to approximate a solution.

2.1. Sampling

Urban contexts were sampled with the geometries of buildings and streets for realistic conditions in the U.S. cities (Fig. 2). For a city center terrain, the height of buildings varies between 9 m and 60 m, representing 3 to 20 story buildings that may cover major portions of a city. This was based on the building stock for Los Angeles (California), Phoenix (Arizona), and Salt Lake City (Utah) [27]. The buildings in a city center were generally commercial and the area of which was in between 1000 m^2 and 2000 m^2, based on a building survey [28]. For an urban terrain, the height of the buildings varied between 6 m and 10 m and building footages were in between 100 m^2 and 300 m^2 for the typical single family homes [29]. For the street dimensions, major two-way streets were in 15 m wide and minor streets were in 9 m wide, based on typical streets [30,31]. Each street contained the minimum 3 m wide roadways for vehicles and minimum 2 m wide sidewalks for pedestrians. For an industrial terrain, only a handful number of buildings were included, all less than 10 m tall. For an open terrain, no building was included. Trees were not included for avoiding complexities and their high computational intensity in CFD simulations. All buildings were in orthogonal shapes and windows were omitted for simplification.

Conforming the existing terrain descriptions of boundary layer parameters (See appendix), the site area was in 1000 m by 1000 m, within which the generated buildings were randomly located while keeping the buildings' orientations along with street lines. Ten (10) samples were generated for each terrain type, one of which was shown in Fig. 2. A slope was added to the generated terrain samples while keeping the total surface areas of exterior walls and roofs in the constructed buildings. A slope was in one-way, only to represent the dominant slope for simplification. The range of the slope was between $+1/10$ to $-1/10$, which covered the typical city areas in the U.S., being based on the mandate for men-powered vehicle [32] and the U.S. urban street regulation [33].

2.2. Airflow assessment

To assess the samples of urban contexts for their impact on wind downscaling, virtual wind tunnel tests were conducted with CFD simulation. To the sampled geometries of the terrains and topographies, planes were added for defining computational boundaries: inlet, outlet, top, and lateral (Fig. 3). Lateral and top planes were prescribed as symmetry boundary for their minimal impact on the airflow. They were parallel to the general direction of wind flow and placed away from the target buildings, more than 5 times the building height (5H). Inlet and outlet planes were placed 10H away from the nearest building for turbulence development. These settings were guided by the best practice of CFD simulation for urban outdoor environment [34].

For meshing, a sub-process of CFD simulation, triangular and tetrahedral cells was used for their easy adaptation to three-dimensional objects regardless of geometrical complexities of buildings and streets. A surface mesh for each terrain types is shown in Fig. 4. Prism layers were added for surface interaction airflow and building surfaces. The maximum change in grid spacing was equal to or smaller than 20% for smoothness in changes of cell