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Review on Numerical Simulation of Airflow and Pollutant Dispersion in Urban Street Canyons under Natural Background Wind Condition

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ABSTRACT

Observation data show that natural wind has a characteristic of regular time-variation in speed and direction. However, the time-varying inflow conditions are usually simplified as a constant wind profile in simulations on airflow and pollutant dispersion in urban street canyons and/or building cluster. The study on characteristics of urban canopy layer (UCL) flow under time-varying inflow conditions should be further contribute to the understanding of pollutant and energy transport processes in the urban atmospheric environment. In the current work, typical studies on air flow and pollutant dispersion in urban street canyons and building array are reviewed. The time-varying upstream inflows could commonly enhance the transportation of pollutant and energy in actual UCL. Studies have revealed that the variation of natural inflow conditions could be one of the primary factors that influencing the transport efficiency of pollutant in urban street canyons. Perspectives on methods in performing the time-varying inflow conditions are provided as well. Gradual and/or stepped variation of wind data would be expected in numerical simulations.

Keywords: Pollutant dispersion; Natural wind condition; Urban street canyon; Gusty wind; Time-varying inflow.

INTRODUCTION

Due to effects of global climate change and rapid urbanization, there has been an increasing interest in the urban wind environment and pollutant dispersion for a long time. In the recent 30 years, the analysis of urban wind environment has been successfully applied in various fields such as pedestrian wind comfort assessment (Janssen *et al.*, 2013), pollutant dispersion prediction (Xia *et al.*, 2012; Scungio *et al.*, 2013; Nikolova *et al.*, 2014), wind load determination (Solari and Pagnini, 1999), natural ventilation analysis (Hang *et al.*, 2013) for building and urban planning policy decision. Various methods such as numerical simulation, wind tunnel simulation and in-situ observations have been used. Fruitful results on air flow, pollutant dispersion and thermal condition within urban canopy layer, especially in urban street canyons, have been achieved. Some papers have given reviews on simulation of environmental condition in urban street canyons based on different perspectives (Vardoulakis *et al.*, 2003; Ahmad *et al.*, 2005; Li *et al.*, 2006).

Air flow and pollutant dispersion in urban street canyons could be influenced by many factors, such as aspect ratio (Oke, 1988; Hang *et al.*, 2012), building layout (Gu *et al.*, 2011; Lin *et al.*, 2016; Mei *et al.*, 2016; Huang *et al.*, 2017), building roof shape (Theodoridis and Moussiopoulos, 2000; Huang *et al.*, 2016), thermal dynamics (Uehara *et al.*, 2000; Cheng *et al.*, 2009), tree planting (Gromke and Ruck, 2007; Abhijith *et al.*, 2017), traffic flow (Jicha *et al.*, 2002; Zhang *et al.*, 2017), physical modal scale (as indicated by Reynolds number) (Uehara *et al.*, 2003; Zhang *et al.*, 2013b) and boundary condition for simulations (Zhang *et al.*, 2011; Li *et al.*, 2017; Yu *et al.*, 2017). Generally, effects of each single factor have been widely studied, with a lot of useful results proposed. However, the simulation of the air flow and pollutant dispersion characteristics in urban street canyons under natural background conditions is still an ongoing problem. Zhang *et al.* (2013a) by comparing the degree of influence, the inflow conditions and building layouts were highlighted as important factors affecting on the environmental condition in various urban street canyons. Mei *et al.* (2017) also investigated the airflow and pollutant dispersion in street canyons under unsteady thermal environment. The effects of thermal dynamics are important consideration under weak wind conditions. The physical modal scale (indicated by Reynolds number) could play a key role in understanding the airflow and pollution dispersion in deep street canyons. Richter *et al.* (2018) even investigated the interaction of convective gusts with a street canyon in a wind tunnel. Kunz *et al.* (2000) found the microscale flow was strongly affected by the mesoscale meteorological structures with a coupling of mesoscale and microscale model, which was applied in an industrial area in southwestern

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In most studies, inflow wind conditions are generally determined according to the average wind speed and the prevailing wind direction that measured by weather stations, as shown in Fig. 1. Simulated results under the prevailing wind direction and the average wind speed are intended to predict the averaged wind and turbulent conditions in urban street canyons, which would be counterproductive. Zhang *et al.* (2011) compared the simulated results under real time wind conditions and averaged wind conditions, as shown in Fig. 1. Results showed that the average wind stream, pollutant dispersion and turbulence intensity were significantly different under the two kinds of inflow conditions. To investigate the air flow, turbulence and pollutant dispersion characteristics within urban street canyons under natural background wind conditions, the time-varying inflow conditions should be considered. Bilal *et al.*'s (2016) numerical simulation results also suggested that the performance of microscale model was largely dependent upon the inflow conditions.

This paper reviews the characteristic of natural background wind and the effect of inflow conditions on air flow and pollutant dispersion within urban street canyons, with a perspective on methods in performing the time-varying inflow conditions.

NATURAL CHARACTERISTICS OF URBAN BOUNDARY LAYER FLOW

A power-spectrum analysis of horizontal wind speed was made by Van der Hoven in 1956 over a wide range of frequencies by piecing together various portions of the spectrum. There appeared to be two major energy peaks in the spectrum: one peak occurred at a period of about 4 days, and a second peak occurred at a period of about 1 minute, as shown in Fig. 2 (van der Hoven, 1957; Emejeamara *et al.*, 2015).

The peak at a period of about 1 minute illustrated the gusty characteristics of natural wind (Peterka, 1998). Cheng *et al.* (2007, 2011) found regular gusty wind disturbances in urban boundary layer wind field, which occurred at a period of 3–6 min. This was obtained by analyzing the observed wind data of the urban boundary layer that was monitored comprehensively using a meteorological observation tower (as shown in Fig. 3(a)) (Li *et al.*, 2010) at the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAPCAS) in Beijing, China.

Cheng *et al.* (2011) divided the observed wind components (in longitude, latitude and vertical directions) into three parts: basic flow, gusty wind disturbances (intermediate time scales or traditionally called low-frequency turbulence) and turbulent fluctuations (small time scales turbulence). They found the gusty wind disturbances in obviously three-dimensional coherent structures, illustrated as downdraft in the peak period of gusty wind and updraft in the valley period of gusty wind, as shown in Fig. 3(b) (Cheng *et al.*, 2007). The gusty wind disturbances would have more important influence on the mass and energy transport within the UCL (Cheng *et al.*, 2011; Babic *et al.*, 2016; Jacob and Anderson, 2017). However, the analysis on the observed data reflected the natural wind characteristics on the measurement point. More generally, the evolution and spatial distribution of wind field under time-varying inflow condition should be a concern.

In fact, effects of gusty wind have been a concern in many research fields, such as in wind energy engineering (Emejeamara *et al.*, 2015), building wind load (Uematsu *et al.*, 1997; Vickery *et al.*, 2010), aeronautical engineering (Lancelot *et al.*, 2015), flight control on artificial intelligence (Chirarattananon *et al.*, 2017), agriculture (Farquhar, 2000), raining (Choi, 1997), power conductor (Wang *et al.*, 2017). It should be also a concern in studying on urban wind environment and pollutant dispersion within the urban canopy layer (Kunz *et al.*, 2000; Coirier and Kim, 2006; Zhang *et al.*, 2011; Ahmad *et al.*, 2017).

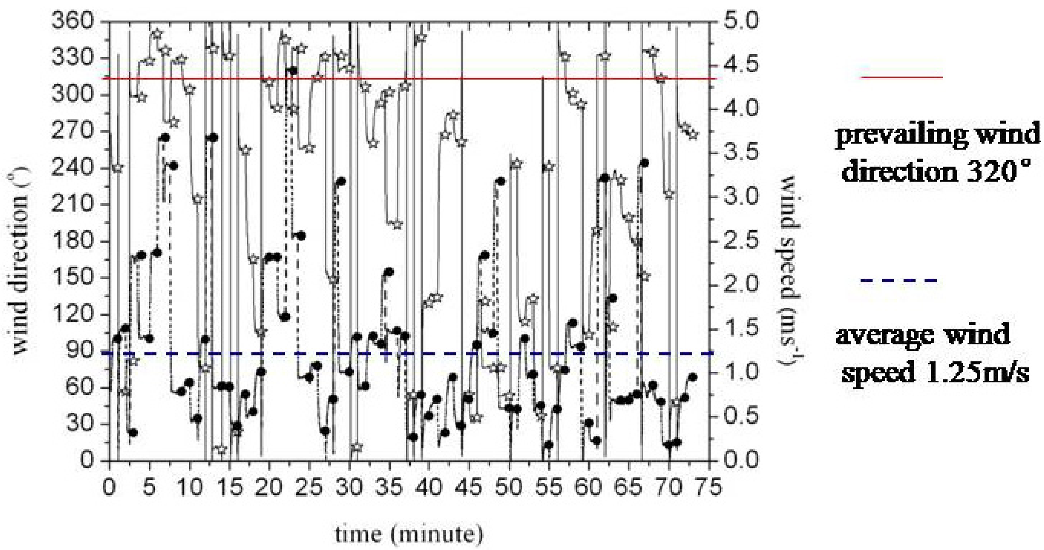


Fig. 1. Measured and simplified wind speed and direction of inflow wind conditions (Star represents wind direction, dot represents wind speed) (after Zhang *et al.*, 2011).

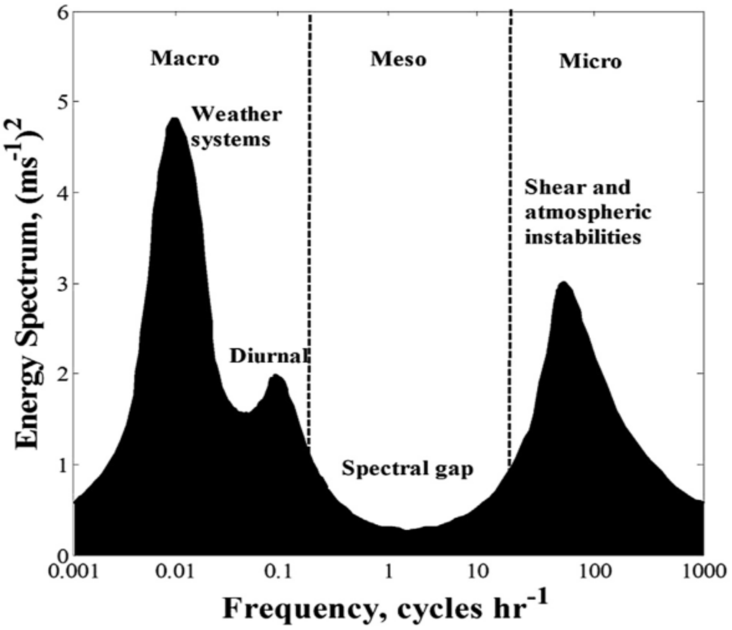
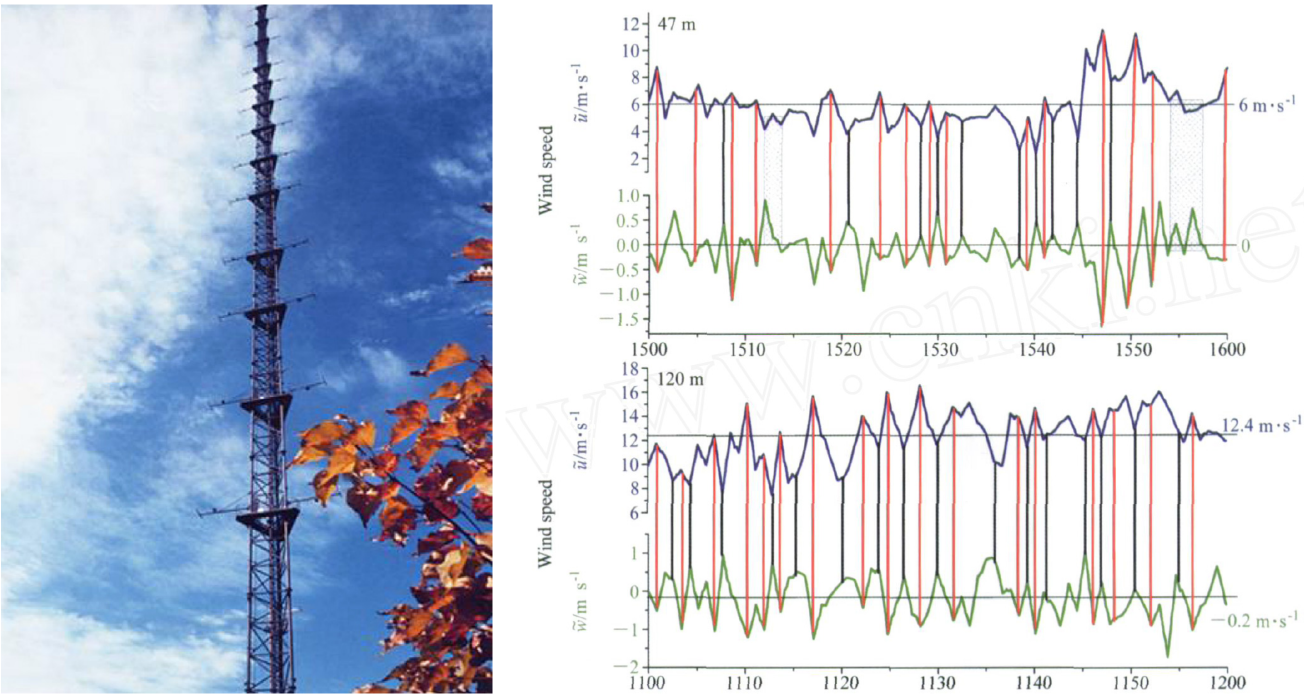


Fig. 2. Frequency distribution of fluctuating wind energy within the internal sub-layer adapted from van der Hover (van der Hoven, 1957; Emejeamara *et al.*, 2015).



(a) (b)

Fig. 3. Beijing Meteorological Tower (a) (Li *et al.*, 2010), and the coherent structure of gusty wind observed on the tower (b) (Cheng *et al.*, 2007).

AIR FLOW AND POLLUTANT DISPERSION UNDER NATURAL BACKGROUND WIND CONDITIONS

Effects of Inflow Conditions

For simulations on airflow and pollutant dispersion in urban canopy layer, average wind speed and prevailing wind direction are usually used in determining the inflow conditions. However, this would neglect the main properties of the natural background wind, due to the time-varying characteristics of wind speeds and directions. For a selected study area, airflow and pollutant dispersion characteristics would vary according to the variation in wind direction (Moonen *et al.*, 2012; Hang *et al.*, 2013; Gousseau *et al.*, 2015). The airflow pattern and pollutant dispersion characteristics in urban street canyons are also different under various inflow wind speeds (Memon *et al.*, 2010; Maruyama *et al.*, 2013; Zhang *et al.*, 2015; Li *et al.*, 2017). Even the inflow turbulence intensity would have an effect on wind characteristics in micro-scale environment (Klein *et al.*, 2003; Maruyama *et al.*, 2013; Yan and Li, 2015).

In case the background wind direction is parallel to the street canyon, airflow within the street canyon like channel flow (see Fig. 4(a)), while multi-vortices airflows dominate the street canyon that perpendicular to the background wind direction. When the background wind flow with an incidence angles between 0–90°, helical flow structures are found within street canyons, as shown in Fig. 4(b) (Moonen *et al.*, 2012).

The change of air change rate (ACH) was also investigated by Moonen *et al.* (2012). The average ACH/h^{-1} in a local domain with volume V m^{-3} was calculated as: ACH = $3600Q \cdot V$, where Q/$m^3 \cdot s^{-1}$ was the average volumetric flow rate out of the local domain via the bounding surface (Moonen *et al.*, 2012). The variation of background wind directions and wind speeds not only have effects on flow patterns within street canyons, but also affect the turbulence, ACH and pollutant dispersion characteristics.

However, most of former studies on effects of wind direction or wind speed were carried out under a series of scenario simulations for typical events, without continuous simulations. Wang (2017) compared the daytime variation of air flow in an urban street canyon under both scenario and continuous simulations. The averaged wind speed and temperature inside the street canyon was shown to be different. Thus, to recur the evolution progress of air pollution in urban street canyons, the continuously simulation under natural background environment condition would be required.

Mei *et al.* (2017) simulated the airflow and particle dispersion in street canyons under unsteady thermal environment with sinusoidal variation. The two-dimensional model of step-up building layouts was applied, to study the dynamic characteristics of instantaneous airflow, the dimensionless ACH and the turbulent kinetic energy (TKE) in the different canyons. The results demonstrated that the stream function within the street canyons exhibited a periodic shift over a day, and the flow morphology gradually evolved from paralleled bilateral vortexes into a row of vortexes, particularly when the ground temperature increased. The fluctuating wind pressure on a 3D square cylinder under turbulent inflow conditions was simulated with large eddy simulation (LES) (Maruyama *et al.*, 2013), where the turbulence data from PIV was used. Quantified inflow uncertainties on wind engineering flows and pollutant dispersion in urban areas were also investigated, where the uncertain inflow parameters were defined by wind speed, wind direction and the aerodynamic roughness (Garcia-Sanchez *et al.*, 2014; Gorle *et al.*, 2015; Garcia-Sanchez *et al.*, 2017).

All these studies have revealed that inflow conditions, even the turbulent fluctuation, can significantly affecting on the flow and pollutant dispersion characteristics in microscale numerical models.

Progress on Simulation of Airflow and Pollutant Dispersion under Natural Background Wind Condition

Natural background wind is time-varying in speed and direction. The simulation of airflow within an urban street canyon under natural background wind condition is an unsteady process. Simulation on wind environment and pollutant dispersion under natural background wind condition with a microscale model is still rare. Generally, the natural background wind conditions could be supplied in two different approaches: (i) using observation obtained from a weather station (Walton *et al.*, 2002a, b; Tewari *et al.*, 2010; Zhang *et al.*, 2011; Li *et al.*, 2016) and (ii) using mesoscale output data (Tewari *et al.*, 2010; Wyszogrodzki *et al.*, 2012; Miao *et al.*, 2013; Kwak *et al.*, 2015; Temel *et al.*, 2018). Especially in recent years, the coupling methods of microscale model with a mesoscale model were widely developed.

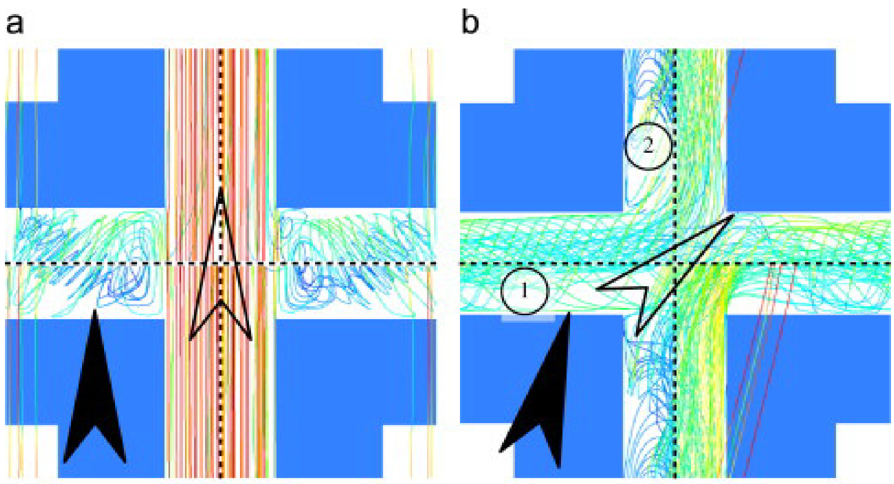


Fig. 4. Streamlines in the street network for different incidence angles. (a) shows the channel flow in the parallel street canyon and the vortices in the perpendicular street canyon; (b) shows the helical flow structures when the background wind flow with an incidence angles between 0–90° (from Moonen *et al*., 2012).

Zhang *et al.* (2011) simulated airflow and pollutant dispersion within an urban street canyon under real-time background wind conditions for a period of 1 hour, with a large eddy simulation model. In their simulation, the background wind conditions were prescribed according to the measured wind velocities and directions on a weather station per minute, as shown in Fig. 1 (Zhang *et al.*, 2011). Large scale vertical convections were found within and above the street canyon. Average wind velocity, pollutant concentration and vertical turbulence transport (VTT) of pollutant were compared under the real-time boundary conditions (RTBC) with those under the stable boundary conditions (SBC), respectively. Under the RTBC, more pollutants were transported to areas above the canyon, thus the average pollutant concentration within the street canyon under RTBC was generally lower than that under SBC. The most significant effect was on the VTT of pollutant. The values of VTT of pollutant under the RTBC were generally one order of magnitude higher than those under the SBC. Under the time-varying boundary wind conditions, the resolved scale wind velocity would be the main factor that affecting on the pollutant transportation at the roof level. The supplementary material (S1) proposed a short video to show the dispersion of pollutant in urban street canyons under time-varying background wind conditions, which is from Zhang *et al.*'s (2011) simulated results.

The resolved scale vertical wind structures were also investigated in atmospheric boundary layer (ABL) simulations under time-varying horizontal wind velocities (Li *et al.*, 2016). Results revealed that the variation of horizontal inflow wind velocity could induce the vertical air flow in downstream. The vertical air flow was downward when wind gust was during the peak period, while it was upward when the wind gust was during the valley period.

Tewari *et al.* (2010) investigated the urban scale contaminant transport and dispersion by coupling a microscale Computational Fluid Dynamics (CFD) model with a mesoscale model. In Tewari *et al.*'s (2010), the two different approaches of supplying initial and boundary conditions as mentioned above were considered. The prediction of contaminant transport and dispersion by the microscale CFD model was found significantly improved when using wind fields produced by mesoscale model as initial and boundary conditions (Tewari *et al.*, 2010). Recently, a method by coupling mesoscale meteorological model of Weather Research and Forecasting (WRF) and large eddy simulation (LES) or Reynolds-Averaged Navier-Stokes (RANS) models in studying traffic pollutant dispersion within UCL was proposed (Kunz *et al.*, 2000; Miao *et al.*, 2006; Baik *et al.*, 2009; Tewari *et al.*, 2010; Liu *et al.*, 2012; Wyszogrodzki *et al.*, 2012; Miao *et al.*, 2013; Kwak *et al.*, 2015; Zheng *et al.*, 2015; Temel *et al.*, 2018).

Liu *et al.* (2012) studied the micro-atmospheric environment in a local district of Beijing with LES, while the lateral and top boundary conditions were provided by the pre-computed atmospheric flow field from the WRF model in Beijing on 26 October 2009. Temporal evolution of flow structure and pollutant (CO) concentration in the local urban area were simulated, with the time-varying wind velocity and temperature on lateral and top boundaries of entire computational domain of LES were provided by the mesoscale WRF model. The simulated results were found in good agreement with field observation data. The flow features were found to vary significantly in 24 h and were influenced by lateral boundary conditions, including the predominant wind direction and speed as well as temperature profile, in addition to the sun radiation and other physical conditions. Thus the coupling method was suggested necessary for diurnal prediction of the unsteady urban atmospheric flow (Liu *et al.*, 2012).

Zheng *et al.*'s (2015) simulation also revealed that the atmospheric boundary structure could play a crucial role on pollutant dispersion within the building cluster, which determined the potential turbulent diffusion ability of the atmospheric surface layer. The variation in ambient wind direction could significantly affect the dispersion pattern of pollutants, and this would be a more sensitive factor than the ambient wind speed. Generally, the wind field and dispersion pattern within the building cluster are complicated, and cannot be obtained from the simplified ambient wind condition directly (Zheng *et al.*, 2015).

Kwak *et al.* (2015) studied the air quality in a high-rise building area of Seoul, using a CFD model coupled with WRF and chemistry-transport model. The spatial variability near the surfaces were strongly associated with the heterogeneity of mobile emission on roads, whereas the spatial variability near the top of high-rise buildings were strongly associated with the heterogeneity of building geometry. Such coupling methods were also used in many other city areas, e.g., Oklahoma City (Tewari *et al.*, 2010; Wyszogrodzki *et al.*, 2012; Temel *et al.*, 2018), Ludwigshafen and Mannheim in southwestern Germany (Kunz *et al.*, 2000). The coupling method between mesoscale and microscale models were investigated as well (Kunz *et al.*, 2000; Wyszogrodzki *et al.*, 2012; Temel *et al.*, 2018).

Generally, methods of coupling local scale CFD with mesoscale WRF models, was able to demonstrate the atmospheric flow features, such as the enhancement of turbulence and the thermal transport under time-varying natural background wind conditions. It also revealed that the performance of microscale model was significantly influenced by the quality of mesoscale winds as input (Bilal *et al.*, 2016). Thus the coupling methods and the performing on time-varying boundary conditions should be vital.

PERSPECTIVE ON METHODS OF PERFORMING TIME-VARYING BOUNDARY CONDITIONS

Performing the time-varying inflow boundary condition has a great significance on simulation of urban boundary layer wind environment and pollutant dispersion. However, studies under time-varying inflow conditions are still rare, as simulation of time-varying boundary condition is difficult to replicate and perform under control condition.

When modelling airflow around a building, even if under the stable inflow conditions, the results can reflect the statistical turbulence, if only appropriate distance was given before the building (Tominaga *et al.*, 2008) or the special turbulence generation scheme was applied (Lund *et al.*, 1998; Klein *et al.*, 2003; Maruyama *et al.*, 2013). However, the gusty wind should be considered in the inflow boundary conditions (Cheng *et al.*, 2011; Richter *et al.*, 2018). As the gusty wind may occur at a period of 1–6 minutes (van der Hoven, 1957; Cheng *et al.*, 2011), the inflow wind should be a time-series of wind in periods of several minutes. The former studies have provided several methods to perform the time-varying inflow condition.

In-situ Measured Wind Conditions

As performed by Zhang *et al.* (2011), measured wind velocities and directions above building roof could be used to determine the inflow conditions with gusty wind considered, where a power law was used in determining the vertical distribution of wind speed (Pavageau and Schatzmann, 1999; Zhang *et al.*, 2011). The vertical distribution of wind speed could also be observed by sounding sites (Tewari *et al.*, 2010). If wind condition only measured on a single site, the measured wind data were generally used to sustain the inflow condition. The measured wind data was averaged per minute, giving a time series of wind data. In fact, many wind sensors could record output wind data per several minutes directly. Thus, getting the time series wind data would not be difficult. However, there is serious need to control the wind data variation in numerical simulations. Generally, gradual or stepped variation of wind data would be expected, as illustrated in Fig. 5(a), but to control the variation process of inflow wind is difficult and important for numerical simulations.

For the stepped variation case, it means the wind speed would be changed from one value to another in a very short period of time. When this change process performed in numerical simulation, numerical divergence would be occurring probably. To prevent the numerical divergence in performing the stepped variation process in simulations, the variation of wind speed could be slow down, as shown in Fig. 5(b) (Zhang *et al.*, 2011). In performing the gradually variation process, Liu *et al.* (2012) keep the wind speed in linear variation in a period of time (e.g., 5 minutes).

Couple With Mesoscale Models

As mentioned above, the time-varying inflow condition for micro-scale environment simulation could be derived from mesoscale meteorological models (Kunz *et al.*, 2000; Liu *et al.*, 2012; Wyszogrodzki *et al.*, 2012; Zheng *et al.*, 2015; Sanchez *et al.*, 2017). In such kind of multi-scale simulations, the coupling method between microscale and mesoscale models should be mentions. Kunz *et al.* (2000) mentioned the coupling method consisted of three elements, including a 3D spatial interpolation scheme, a spatial adjustment of values, such as wind velocity and temperature, within the surface layer, and the formulation of the lateral boundary conditions to introduce the interpolated values into the microscale models. In the interpolation scheme, the fraction of a partial volume to the whole volume was taken as the interpolation weighting factor. The similarity theory was used in adjusting the interpolated values, where the microscale wind speed in the surface layer is either calculated by a power law or a logarithmic law (Kunz *et al.*, 2000). Differences between the turbulence models in mesosacle and microscale simulations should be also coupled (Temel *et al.*, 2016, 2018). Using the reported wind data from the mesoscale meteorological model, e.g., WRF, the lateral and top boundary conditions in the micro-scale simulations, varying with time, could be performed, for example, changing gradually from one wind data to the next. In this case, the variation of inflow conditions would be assumed in gradually variation style, as shown in Fig. 5(a). The open/ zero-gradient boundary conditions (Wyszogrodzki *et al.*, 2012) could be applied at outflow boundaries. In most of the reviewed literatures, the gradual variation mode (or linearly interpolation method) was often selected to trace temporal variation of the inflow wind (Tewari *et al.*, 2010; Liu *et al.*, 2012; Wyszogrodzki *et al.*, 2012; Cui *et al.*, 2013).

Some Other Methods

The two methods introduced above have been validated

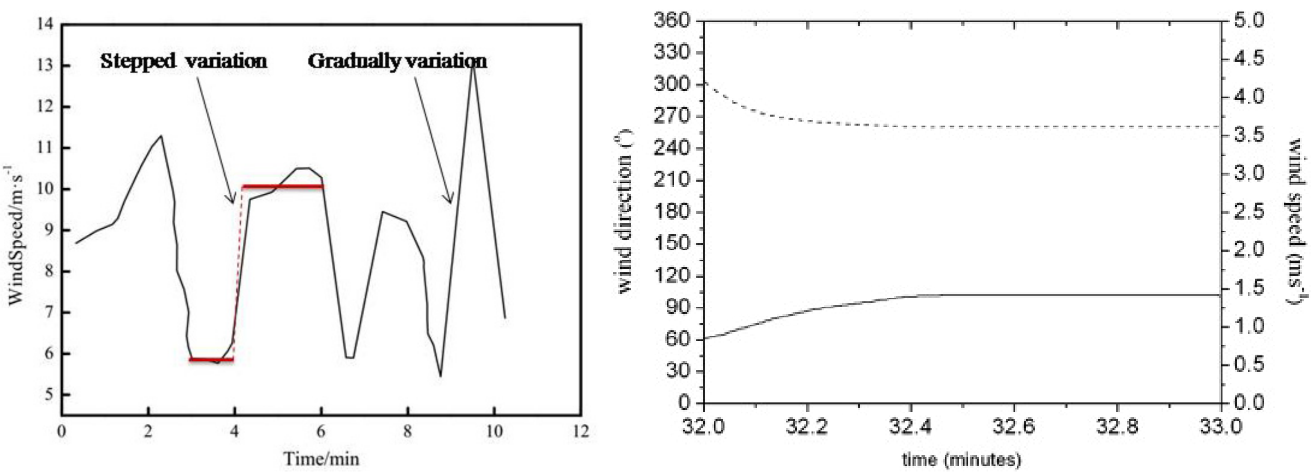


Fig. 5. Illustration of two kinds of wind data variation, gradual and stepped variation (a), and the variation of upper boundary wind velocity (solid line) and wind direction (dash line) between two measured wind values in a simulation case (Zhang *et al*., 2011).

as feasible for micro-scale simulations. However, there are some other methods that have been proposed for some other purposes, which could be useful for simulating the natural background wind conditions (Thorarinsdottir and Johnson, 2012; Garcia-Sanchez *et al.*, 2014; Valero *et al.*, 2014; Gorle *et al.*, 2015; Lucas *et al.*, 2016; Efthimiou *et al.*, 2017; Garcia-Sanchez *et al.*, 2017).

Thorarinsdottir and Johnson (2012) proposed a method for forecasting wind gust, which could contribute to the determination of the wind gust probability. Valero *et al.* (2014) also studied the forecasting method of wind strength from observed daily wind gust data. These statistic methods would be useful for future studies. Garcia-Sanchez *et al.* (2014, 2017) investigated the quantifying inflow uncertainties from an ensemble of 729 RANS simulations.

Overall, methods in performing time-varying boundary conditions need further investigations. Firstly, all the methods should be validated according to measurements. Fortunately, some wind tunnel or in-situ measured wind and/or pollutant concentration data have been published, which may be helpful in model validations (Kunz *et al.*, 2000; Liu *et al.*, 2012; Brown *et al.*, 2013; Wyszogrodzki *et al.*, 2012; Zhang *et al.*, 2012; Garcia-Sanchez *et al.*, 2014; Sun *et al.*, 2016; Tse *et al.*, 2017). Secondly, effects of variation styles of inflow wind speed and/or direction on airflow characteristics within urban street canyons should be investigated. As pointed in this work, inflow wind speed and/or direction might change in a slow or fast ways. Simulated results under these two different variation styles have not been compared. And also, the balances on mass, momentum, and TKE should be satisfied in simulations as well (Kunz *et al.*, 2000; Temel *et al.*, 2018).

SUMMERY

Meteorological observation data show that natural wind has characteristics of regular time-variation in speed and/or direction. Currently, the time-varying inflow conditions are usually simplified as a constant wind profile in simulation on airflow and pollutant dispersion in UCL. Recent studies have revealed that the flow features could vary significantly influenced by lateral boundary conditions, including the predominant wind direction and speed. The values of VTT of pollutant under the real-time boundary conditions are clearly higher than those under the stable boundary conditions. Thus, simulations under natural background wind conditions are of importance.

The time-varying inflow conditions can be performed through in-situ measured wind data or via forecasting data obtained from the mesoscale model. Gradual and/or stepped variation styles of wind data would be expected. To prevent the numerical divergence in simulations, the controlling on variation process of inflow wind is important.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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