CWE-8
June 7-11, 2026
London, ON, Canada

Effect of coherent structures occurring in urban boundary layer during a typhoon on turbulent fields within the urban canopy

Hidenori Kawai [a], Tetsuro Tamura[b]

[a]*Ochanomizu Unversity, Bunkyo, Tokyo, Japan, kawai.hidenori@ocha.ac.jp*
[b] *Yokohama National University, Yokohama, Kanagawa, Japan, tamura-tetsuro-dr@ynu.ac.jp*

SUMMARY

Coherent structures strongly influence peak wind speeds and wind pressures within urban canopies during typhoons, but their characteristics within the urban boundary layer under typhoon conditions remain unclear. This study examines the effect of the coherent structures on turbulent field within the urban canopy using LES of the urban boundary layer during Typhoon Lan (2017). First, the vertical profile of wind velocity and direction are analysed and compared with the profile in LES with a turbulent boundary layer inflow. Then, a reduced order model of the urban turbulent field is constructed using proper orthogonal decomposition. From this model, turbulent structures associated with vertical meteorological mixing and those induced by surface roughness are identified and classified. Finally, the coherent structures affecting the turbulent field within urban canopy are discussed.

Keywords: *Meteorological disturbance, boundary layer, urban canopy, LES, coherent structure*

1. INTRODUCTION

In urban areas during typhoons, the coherent structures that develop over buildings significantly influence the peak wind speeds within the urban canopy and the wind pressures acting on buildings. Although previous studies have clarified the coherent structures above buildings and those within the surface layer by observations and numerical simulations, the characteristics of coherent structures within the urban boundary layer under typhoon conditions remain insufficiently understood. This study examines effect of coherent structures occurring in urban boundary layer during a typhoon on turbulent fields within the urban canopy. First, we clarify the distributions of wind velocity and direction in the urban boundary layer by comparing LES results based on both typhoon inflow condition and inflow condition of turbulent boundary layer. Next, turbulent structures derived from vertical mixing in the meteorological field and coherent structures induced by surface roughness are classified and the types of coherent structures affecting the turbulent flow within the urban canopy will be discussed.

2. METHODOROGY

Figure 1 shows the outline of the analysis method for the urban boundary layer under typhoons. In this study, the spatial filtering and rescaling method proposed by the authors is applied to the meteorological field for Typhoon Lan in 2017 obtained by the meso-scale meteorological model (WRF-LES) (Nakajima et al., 2022). Furthermore, the obtained spatio-temporal data in driver region is used as the inflow boundary condition of broad-region LES. The target meteorological field has a vertical distribution of wind direction, and inflow from the side may occur depending on the height. Thus, the temporal and spatial data of wind velocity from the SSE and WSW planes are connected as inflow boundary conditions of broad-region LES. For broad-region LES, turbulent field resolving topography and buildings are computed by Building Cube Method (BCM) (Jansson et al, 2018) (Main region, shown in figure 2). Minimum spatial resolution is 2.75m.

Figure1(b) shows inflow condition on SSE plane. In this study, the results using inflow condition of Case 2 based on meteorological field are compared with the previous results (Kawai and Tamura et al.,2022) using inflow condition of turbulent boundary layer (TBL) (Case1 in figure 2(a)).

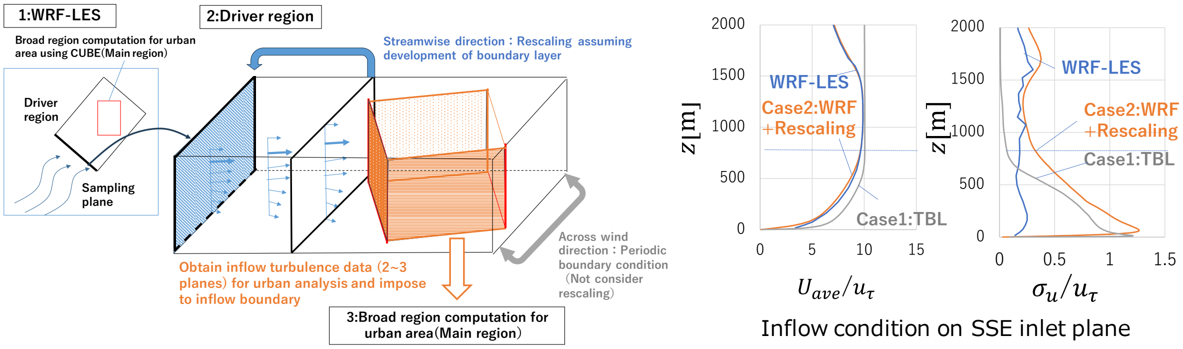


Figure 1: Analysis method of urban boundary layer under typhoon

3. CHARACTERISTICS OF URBAN BOUNDARY LAYER

In this section, change of vertical profile on average velocity and turbulent intensity at B1-B6 corresponding to development of boundary layer is discussed by comparing 2 cases different in inflow condition. Figure 2 presents the distribution of the averaged wind velocity U, which is SSE→NNW component, and Figure 3 shows its vertical profiles. In the LES with a turbulent boundary layer inflow without meteorological fields, a velocity deficit appears near point B3 due to coastal high-rise buildings, and the boundary layer develops up to about 800 m. In contrast, in the case with inflow including meteorological field (Case2), although a similar velocity deficit occurs, development of boundary layer is suppressed.

As a result of comparison of vertical profiles of wind velocity from the coast to the urban district, the vertical profile of u in both cases shows nearly identical in leeward area of the high-rise buildings (B3 and B5) within the urban canopy layer, indicating the dominant influence of surface roughness. However, in Case2, the cross-wind and vertical velocity components differ due to vertical distribution of wind direction in the meteorological field. For the same reason, turbulence intensity above 400 m is higher than in the Case1 using turbulent boundary layer inflow.

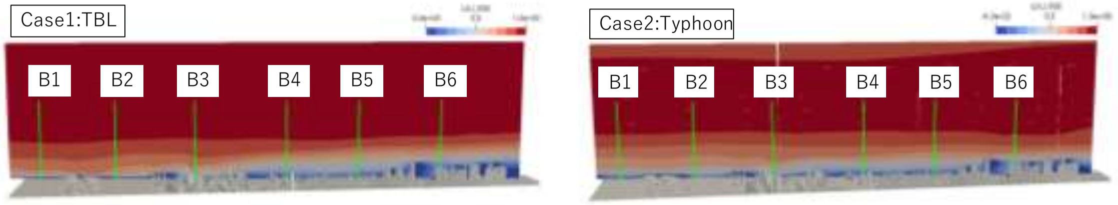
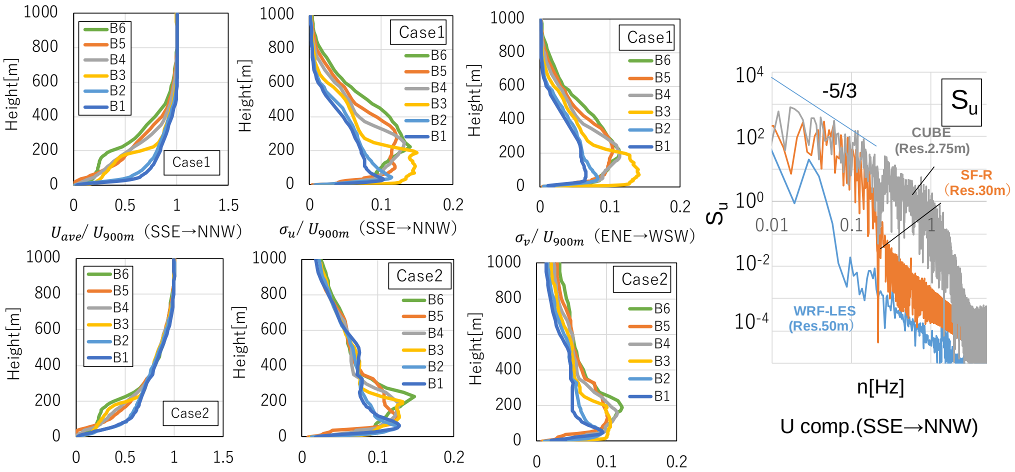


Figure 2: Vertical section of averaged wind velocity
(Case1: TBL inflow condition, Case2: Inflow condition based on Typhoon meteorological condition)

Figure 3(b) shows power spectrum density in urban area in case 2. In inflow data obtained by SF-R method, high-frequency fluctuation of velocity which is not reproduced in WRF-LES appears. Then, in LES result including heterogeneous roughness effect (grey legend of CUBE), region of inertial sub-range is extended to higher-frequency region by resolving building and topography with finer grid resolution.



(a) Vertical profile of wind velocity

(b) Power spectrum of u (Case2, height of 150m)

Figure 3: Vertical profile of wind velocity and power spectrum of u

4. COHERENT STRUCTURES IN THE URBAN BOUNDARY LAYER

In this study, we focus on a 4 km × 3 km area within the computational domain and discuss the coherent structures that appear over the urban area. Figure 4 shows the horizontal distribution of the velocity fluctuation u' in this 4 km × 3 km region, and Figure 5 presents the vertical distribution of the velocity fluctuations u' and w'. At a height of 200 m, as shown in Figure 4, streaky structure based on shear derived from surface roughness conditions appears at intervals of approximately 300 m. In contrast, at a height of 500 m, larger-scale structure of several hundreds m derived from the meteorological field appears. In the y-z cross-section in Figure 5, high-velocity and low-velocity u' structures can be alternately observed with intervals of around 500 m at the height of 500 m. In w' component, alternating upward and downward motions appear at intervals of several hundred meters over 200m height.

Moreover, in this study, a reduced order model of the turbulent field over the city will be constructed based on the proper orthogonal decomposition (POD). Using this reduced order model, we will classify turbulent structures derived from vertical mixing in the meteorological field and coherent structures due to surface roughness.

5. CONCLUSION

This study reproduces UBL in central Tokyo under typhoon Lan in 2017 and analyzes the characteristics of turbulent structure over heterogeneous roughness in urban areas. As a result of comparison with case using TBL inflow, roughness effect near ground becomes dominant in leeward area of high-rise building cluster for streamwise velocity. However, meteorological structure with a scale of several hundred meters exists over 200m (above surface layer) height and

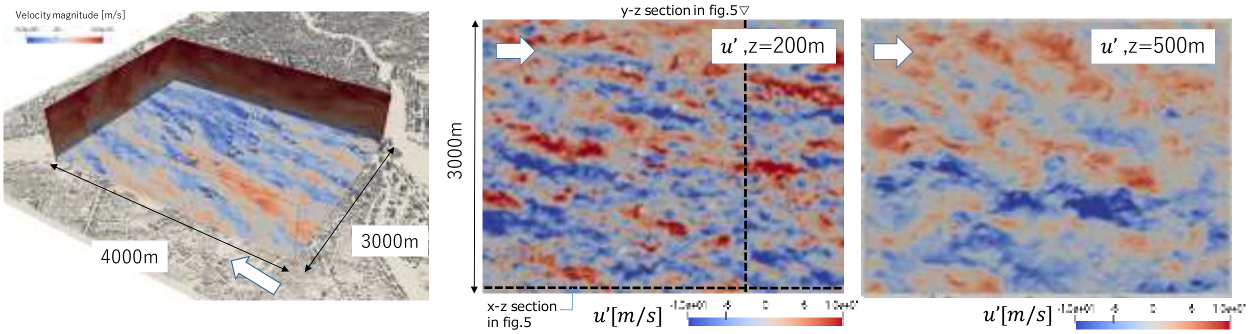


Figure 4: Turbulent field of u' in focused region (case2)

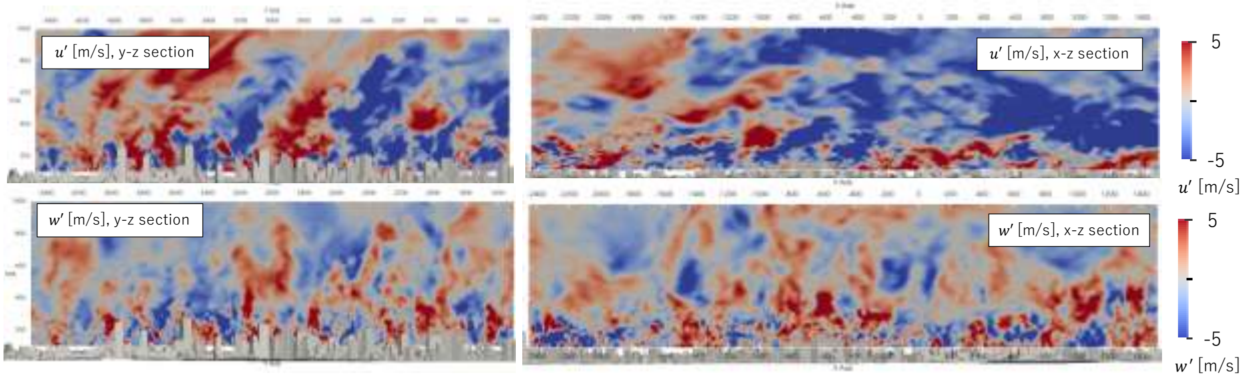


Figure 5: Vertical section of u', w' (Case2)

turbulent characteristics above surface layer are completely different from case using TBL inflow. Also, development of boundary layer derived from high-rise building cluster is suppressed due to meteorological structure above surface layer.

In the presentation, we will classify the turbulent structures arising from vertical mixing in the atmospheric field and the coherent structures induced by surface roughness, based on a reduced-order model obtained through proper orthogonal decomposition (POD). We will then discuss the effect of these coherent structures on the turbulent flow within the urban canopy.

ACKNOWLEDGEMENTS

This research used computational resources of the Fugaku computer provided by the RIKEN through the HPCI System Research project (Project ID: hp210262)

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