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LES FOR URBAN BOUNDARY LAYER USING INFLOW CONDITION INCLUDING METEOROLOGICAL DISTURBANCE OF TYPHOON

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ABSTRACT

This study reveals turbulent structure in broad urban area of Tokyo under strong wind events by LES. First, the simulation results of velocity with inflow conditions using meteorological data are validated by comparison with the observation results. Then, the development process of urban boundary layer (UBL) from coastal area of Tokyo are examined and the effect of meteorological disturbance on the fluctuation of velocity in upper height of atmospheric boundary layer is examined. Finally, various kind of structure in urban boundary layer are examined in each height. The results show that the wake structure from high-rise building clusters remains in several km leeward also in the case with inflow condition using meteorological data.

BACKGROUND

The characteristics of urban boundary layer (UBL) are an important factor for determining the inflow condition in estimation for wind pressure and force. In particular, in the urban area as Tokyo, the area has various roughness pattern including buildings with various heights and high-rise building clusters. Thus, the turbulence characteristics around urban canopy are affected by various roughness condition in urban boundary layer. Generally speaking, in UBL, various kind of structure exists in urban boundary layer. For example, some researchers examine the relation between the roughness parameter and turbulence field for coherent structure above urban canopy (e.g. Coceal et al. 2006). In the higher height, streaky structure which is determined by the scale of atmospheric stability and velocity gradient derived from heterogeneous parameter exists (e.g. Yagi et al. 2016). In the upper area of urban boundary layer, roll type structure which is determined by the scale of boundary layer thickness (e.g. Wurman et al. 1998).

In the estimation of wind pressure and force using wind tunnel experiment and LES, the inflow condition generated mechanically is used, the effect of meteorological fluctuation above urban canopy is not considered generally. This study clarifies the effect of meteorological fluctuation above urban canopy on the turbulence structure from the results of LES for 9km x 9km region of Tokyo central area. In this study, the effect is shown by comparing the simulation cases with the inflow condition with and without meteorological fluctuation.

METHODOLOGY

Outline of BCM

In order to accurately predict the wind flow in canopy layer of large urban area, we introduce LES based on BCM (Building Cube Method) which is formulated on the very fine Cartesian mesh system. In this study, CUBE code which is developed by RIKEN R-CCS is used (Jansson et. al, 2018). Recent high-performance computing (HPC) technique has developed distinctly, so high-resolution computation becomes able to be applied to flows around a complicated configuration such as actual urban area. In this case we have to deal with buildings, vegetation and street etc. as a part of numerical model. Actually LES using the Cartesian coordinate encounters the non-correspondence of directions between the street lines and the discretized mesh lines. Very fine mesh system by BCM can solve this problem, supported by the external forcing technique at the boundary named IBM (Immersed Boundary Method). Also, BCM uses the mesh system consisting of cubes and cells in the Cartesian grid. Each cube has 16 by 16 by 16 cells, and then the algorithm of computation is quite simple. As a result, the efficient solver on high performance computing is realized for parallel algorithm where the load balance is appropriately obtained at each core.

Calculation condition of target domain

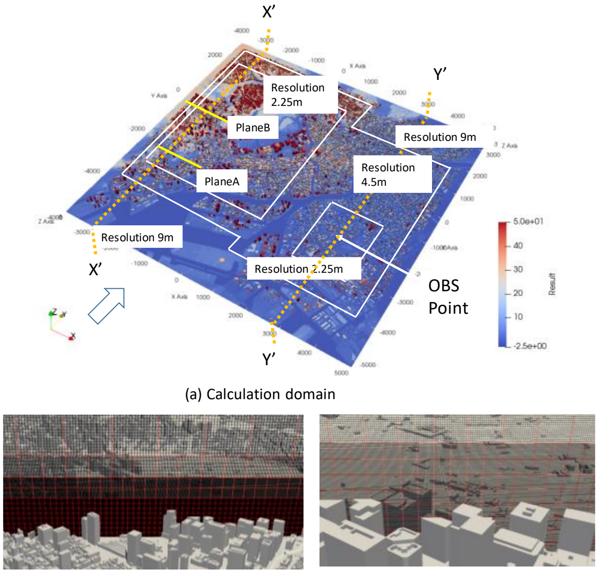
This study carries out the numerical simulation for Tokyo, and configuration of building and topography is reproduced by GIS data and altitude data by Geospatial Information Authority of Japan. In this study, the sizes of the computational domain are 9km x 9km(fig 1(a)). The finest resolution is determined as 2.25 meter and grid number is approximately 960 million.

Making inflow condition

For inflow condition, two type of inflow condition is imposed to boundary condition of calculation domain. One is turbulent boundary layer (TBL) assuming boundary layer above roughness condition. This inflow condition is generated by driver region computation with semi periodic condition proposed by Nozawa and Tamura (2002).

The other is inflow condition including meteorological fluctuation. Meteorological field is generated by meteorological model (WRF-LES) and the field for Typhoon Lan which passed over Tokyo in October 2017. Meteorological simulation by WRF-LES is carried out by 5-domain nesting simulation. The minimum spatial resolution is

50 m. However, it is difficult to generate velocity with sufficient fluctuation for reproducing turbulent field around urban canopy. In this study, inflow condition is generated by Kawai and Tamura (2020). In this method, high-frequency component is added to the results of meteorological model (WRF-LES) using the method using spatial filtering and rescaling technique in semi-periodic condition (Fig. 2).



(a) Calculation domain

(b)Grid division (Red line: Cube, Black line :Grid)

Figure 1. Calculation domain and grid

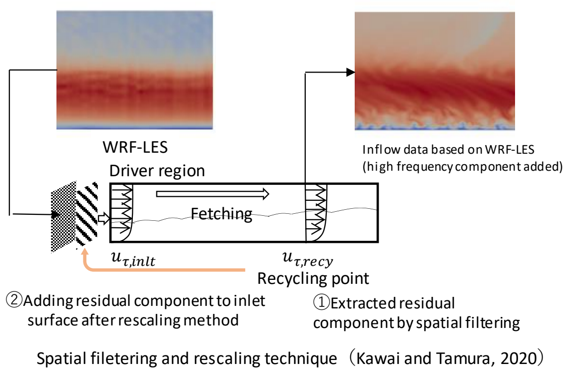


Figure 2. Method for making inflow condition using spatial filtering rescaling technique

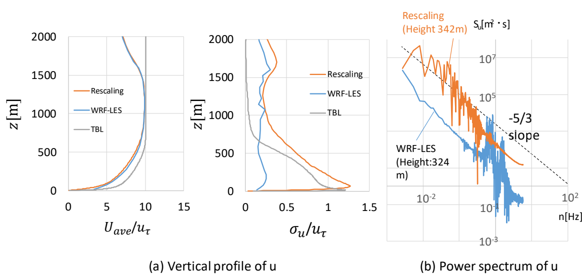


Figure 3. Inflow condition for broad region simulation

The figure 3 shows time series data and vertical profile of velocity. In the generated inflow condition, velocity with high frequency fluctuation is generated and turbulent intensity increases near ground region (z/δ<1) compared with original WRF-LES results.

TURBULENCE STRUCTURE OF URBAN AREA

Comparison with observation data

First, the simulation results of velocity using inflow conditions of meteorological model are validated by comparison with the observation results by Doppler lidar (Yamanaka et al., 2018) at point P1 in figure 1(a).

Figure 4 shows vertical section of instantaneous velocity field. In the both cases, turbulence from urban blocks occurs from coastal area of target area. As result of comparison, vertical profiles of average velocity obtained by LES using TBL inflow condition and WRF-LES based inflow condition correspond to that of observation data though the velocity overestimates in the height less than 200m (shown in figure 4).

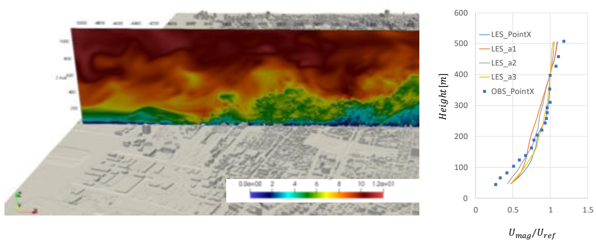


Figure 4 Comparison with observation data

Development process of urban boundary layer

This study analyses the development process of urban boundary layer (UBL) from coastal area of Tokyo. Figure 5 shows vertical section of U_{ave}, u_{rms} in Section X-X'(location is shown in figure 1(a)). In the case with TBL inflow case, the result shows that the effect of turbulence which is induced from low-rise urban blocks contributes to UBL development and the thickness of urban boundary layer reaches over 700m in TBL inflow case. Also, as a result of comparison of the velocity fields by 2 inflow conditions, it is shown that the simulation result using inflow condition based on WRF-LES includes large scale of meteorological fluctuation in upper height of boundary layer. In figure5, large u_{rms} value remains in upper height of boundary layer around 1000m height in the case of WRF-LES based inflow condition.

Figure 6 shows instantaneous velocity (u,v,w) in PlaneB (location is shown in figure 1(a)). The extracted velocity which is obtained from LES using inflow condition of TBL includes turbulence from urban roughness condition in addition to turbulence of inflow condition. The fluctuation appears at the height less than 800m. Then, in LES using inflow condition based on WRF-LES, large scale of fluctuation appears in the upper height of atmospheric boundary layer and the fluctuation remains in the height over 1000m. Also, in the inflow condition based on WRF-LES, average of v component changes depending on height. The value of v is negative in the height less than 400m and positive in the height over 400m mainly.

Figure 7 shows vertical profile of velocity in sampling planes for LES using inflow condition based on WRF-LES. Vertical profile of velocity imposed to inlet plane is maintained in sampling point of planes A,B though the colioris force is not considered in the the calculation domain of broad region analysis and the value of v decreases by 1.0-1.5 of v/u_τ. Also, focusing on the rms value, the rms value is larger than that of inlet plane due to turbulence from actual urban configuration.

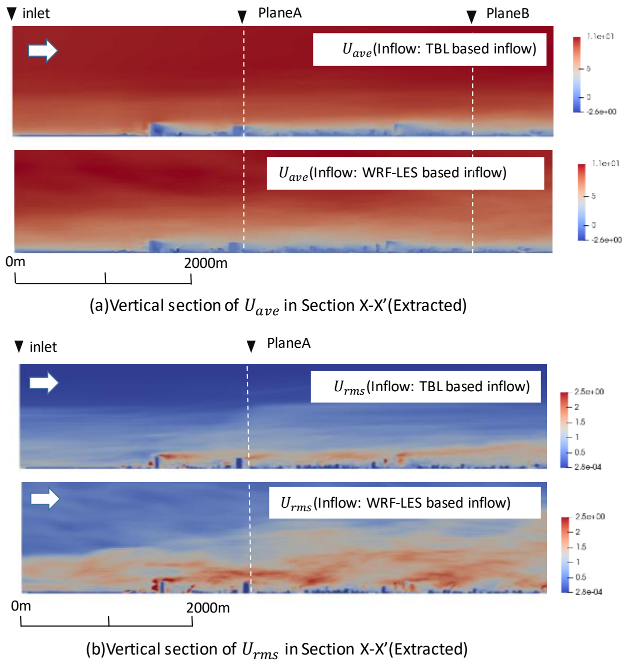


Figure 5. Vertical section of Uave and Urms

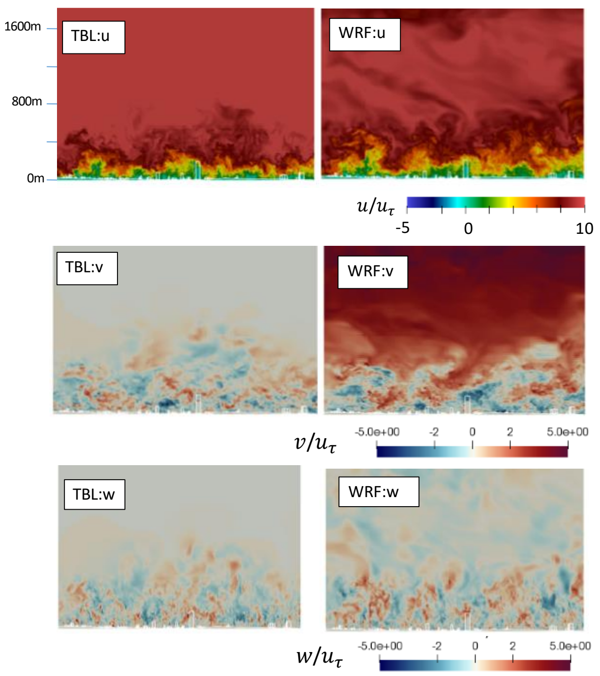


Figure 6. instantaneous velocity u,v,w at Plane B

Turbulent structure in urban boundary layer

In this part, various kind of structure exists in urban boundary layer are examined in each height. In particular, meteorological disturbance has large scale of fluctuation in upper area of atmospheric boundary layer and the effect on turbulent structure at each height are examined. Focusing on the height around 100m height in the case with TBL inflow condition, separated shear layer occurs from several high-rise building clusters with over 100m height of building. The fluctuation from high-rise building clusters remains in several km leeward area (figure 5(b)).

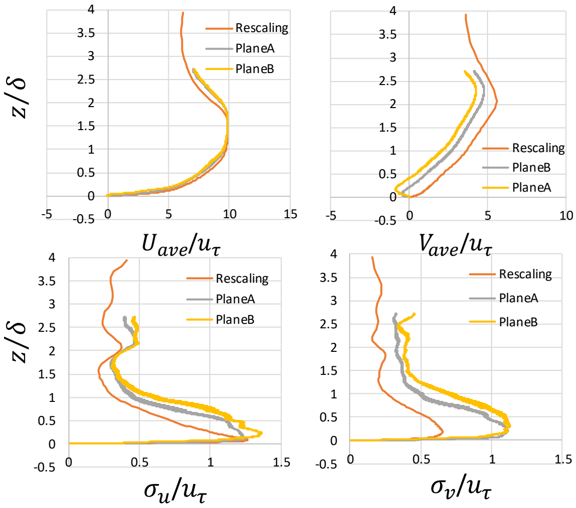


Figure 7. Vertical profile of velocity in sampling planes (WRF-LES based inflow condition)

Also, in the case with WRF-LES based inflow condition, the structure of fluctuation from high-rise building clusters is not clear compared with the case with TBL. This is because the structure of fluctuation from high-rise building clusters exists in the large scale of fluctuation which is derived from meteorological disturbance. However , u_{rms} distribution in figure 5(b) implies that the fluctuation effect from high-rise building clusters remains in several km leeward area.

Figure 8 shows horizontal plane of instantaneous velocity at 50m, 150m,250m. In the cases of LES using TBL inflow, wake structure goes x direction. In particular, streaky structure derived from high-rise building clusters appears clearly at height of 150m. Also, structure of low velocity connecting with streaky structure derived from high-rise building clusters remains at height of 250m. On the other hand, in the case of inflow condition based on WRF-LES, wind direction and direction of wake region and streaky structure is different. In the height of 50m, wind direction is almost S, but it changes to SSW in the process of fetching in the calculation domain of broad region. In addition, wind direction at the height of 150m,250m is almost SE because wind direction depends on the height in typhoon condition. In the typhoon conditon, air percel is affected by colioris force and centifugal force.

Furthermore, in the case of inflow condition based on WRF-LES, turbulent structure is affected by vertical mixing occurring in upper height of urban boundary layer. In fig. 8(d),(e), large structure of high velocity appears. These structures occurs by transporting momentum of upper height with high velocity to lower area by vertical mixing.

Figure 10 shows power spectrum density of velocity in sampling plane B in the cases of LES using TBL inflow and inflow condition based on WRF-LES. In u,v,w component of velocity, fluctuation satisfies 5/3 lows until order of 0.1 Hz (corresponding to time scale of several seconds). In u component, difference of Su is not clear between 2 inflow cases. On the other hand, in v,w component, level of Sv, Sw in LES using inflow condition based in WRF-LES is heigher at the frequency less than 0.01Hz. In particular, this tendency is more apparent in higher height, the difference of Sv,Sw is large at the point of 220m.

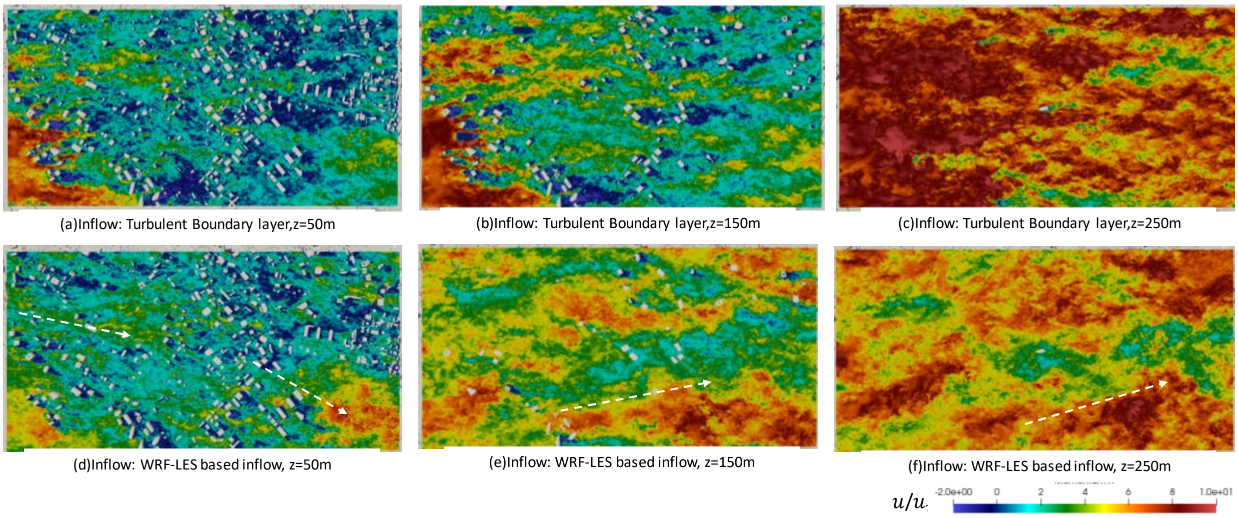


Figure 8. Horizontal plane of instantaneous velocity at 50m, 150m,250m

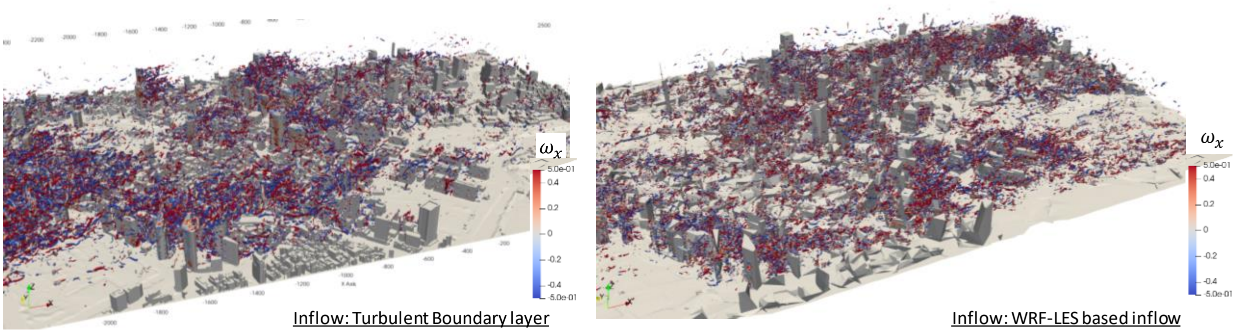


Figure 9. Isosurface of Q criterion (Q=0.1) colored by x component of vorticity

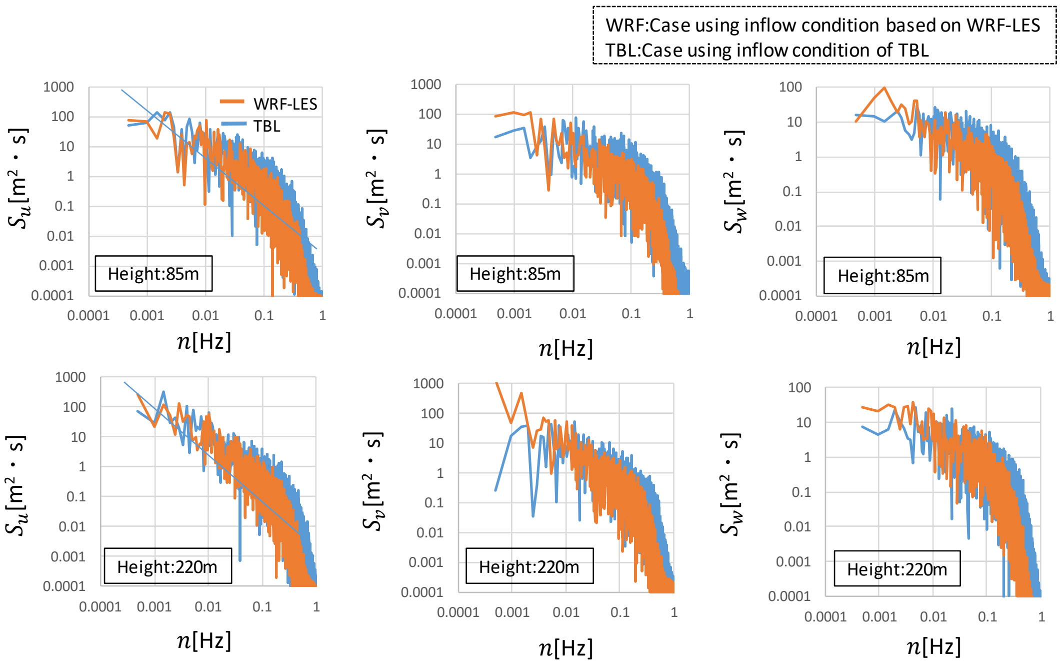


Figure 10. Power spectrum density of velocity in plane B

CONCLUSION

In this study, the effect of meteorological disturbance above urban canopy on the turbulence structure for 9km x 9km urban area of Tokyo is clarified by comparing with the results with TBL inflow condition. First, the development process of urban boundary layer (UBL) from coastal area of Tokyo are examined and the effect of meteorological disturbance on the fluctuation of velocity in upper height of atmospheric boundary layer is examined. Then, various kind of structure exists in urban boundary layer are examined in each height. In this paper, the effect of meteorological disturbance on the wake structure from high-rise building clusters are examined.

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