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ENVIRONMENTAL TURBULENCE IN URBAN BOUNDARY LAYER -LES AND FIELD MEASUREMENT-

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ABSTRACT

This paper describes the environmental turbulence in urban boundary layer. Using the field measurement data and LES data for wind velocity above urban area, vertical profiles of time-averaged, fluctuating and peak wind velocities are clarified, relating with various roughness parameters at urban surface. Also, different types of coherent structures in wind turbulence which are formed according to the altitude are elucidated. The origins on formations of various vortices are found out and physical process for generating coherent structures is discussed. Concerning LES, high performance techniques are employed for the very large computation of wind over urban roughened surfaces representing a direct shape of buildings, houses and vegetation.

Recently in Japan, strong-wind disaster frequently occurred in actual city under an attack of typhoon. Sometimes, the local peak velocity relating to the disaster has been recognized above and within urban canopy. However detailed characteristics of turbulent wind around urban geometry with heterogeneity have not been completely understood yet. This study presents the LES statistics of a turbulent boundary layer above the much roughened surface like TOKYO. The numerical results are validated by comparison with observation data in the atmospheric turbulent boundary layer over the TOKYO area. Also, LES reveals the occurrence of the instantaneous maximum peak of velocity fluctuation and clarify its profile with relation to various roughness patterns at each location.

INTRODUCTION

Over urban area covered by buildings, streets, houses and vegetation, a turbulent boundary layer develops but its turbulence structures are not completely understood yet. In the case of a turbulent boundary layer which is formed above actual urban area, a uniquely distinctive condition is imposed. The ratio of the boundary layer depth to the averaged-height of roughness obstacles is small compared to that of conventional rough-wall turbulent boundary layer in fluid mechanics. Also, each shape of a roughness is very complicated and its height is changed largely. Previous researches have thus far dealt with the rough surface with uniformly arrayed blocks. Roughness parameters related with mean wind velocity profiles have been determined by wind tunnel experiments. However it is very difficult to determine such a parameter for the actual urban turbulent boundary layer. It can be presumed that completely different structures appear in the case of turbulence within an urban boundary layer. Grimond et al. (1999) proposed the roughness parameters based on full scale measurement data of wind velocity field.

Concerning the Large Eddy Simulation (LES), two of the present authors performed the numerical simulations of wind flows over urban surface at Tokyo (2017). Wind characteristics and turbulence structures over urban roughness were investigated and fitted to power law of wind profile. Power index obtained numerical simulation tends to become larger and especially large velocity deficiency occurs at the near-ground region in a city. In order to solve the inconsistency of wind profile between LES data and the previous data which is practically used for wind resistant design of buildings and structures, the validation of LES for environmental turbulence in urban turbulent boundary layer is strongly required.

The present research analyses the field measurement data of wind velocity obtained in the center of Tokyo by using the lidar. Also, LES is carried out for urban boundary layer. Numerical model is based on the Building Cube Method (BCM) and Immersed Boundary Method (IBM) for complicated shape of urban surfaces. Building shape is directly used to represent the bottom boundary conditions of urban area. Numerical model is validated comparing with the field measurement data. Furthermore turbulence structures above urban area is investigated focussing on the coherent structures such as roll patterns, longitudinal vortices or the hairpin structures above the roughness (Figure 1).

As another view for safety in a city, it should be focussed on that environmental wind disaster, related to strong wind gust acting above and within actual urban region, frequently occurs causing severe damage to building surfaces and houses. In particular, strong wind gust drives debris (remaining on the ground or generated by other building surface collapse) to hit and break other building surfaces. For aerodynamic mechanism, the wind gust can be generated by separated flows from heterogeneous buildings (high rise and low rise buildings arranged with highly changeable heights ranging from 10m to 100m) and vortices shedding from the windward buildings. On the other hand, strong wind gust is also derived from turbulent wind field above urban area, and it is the direct cause of serious damage of buildings and structures. For design and safety, the characteristics of wind field and gust in urban boundary layer, including time-averaged, standard deviation of wind velocity, and maximum of instantaneous wind velocity in the realistic urban canopy, should be completely understood. Basically, the wind gust is strongly correlated to the instantaneous velocity peak but not to the pressure fluctuation. So far, there is no experiment and numerical report regarding the maximum of instantaneous wind velocity and its effect and occurrence in the region at the building height. In fact, it is very difficult for field observation to produce the high-resolution observational data which make it possible to obtain the instantaneous peak of velocity. Hence, the LES is performed in the present work with high resolution confined to the heterogeneous surface by various types of buildings and terrain slope. Based on the analysis of turbulent urban boundary layer, the instantaneous maximum characteristics are elucidated with relation to local heteorogeneous patterns. For more accurate numerical confirmation using field observation based on Doppler lidar etc as well, inflow turbulence for LES is generated considering effect by the large-scaled meteorological disturbance and applied.

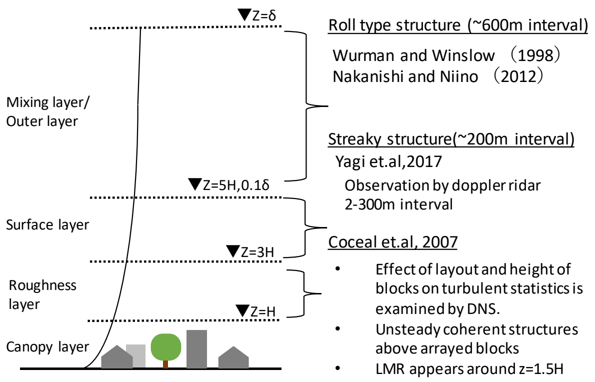


Figure 1. Schematic of urban boundary layer.

HIGH PERFORMANCE COMPUTING BY BCM-LES

Outline of BCM-LES

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 (Onishi et al., 2013). 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 (figure 2). 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.

The urban boundary layer which develops over Tokyo is resolved in a high resolution for the complicated shape of buildings and terrains using LES-based Building Cube Method (BCM-LES) by Onishi et al. (2013). The boundary condition in BCM-LES is imposed using volume constraint IBM developed by Patankar et al. (2000). It shows the advantage in modelling the no-slip boundary condition for complex geometry with highly physical approach.

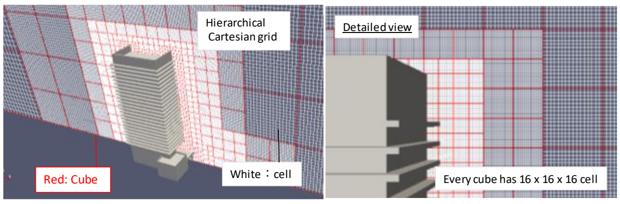


Figure 2. Concept of building cube method.

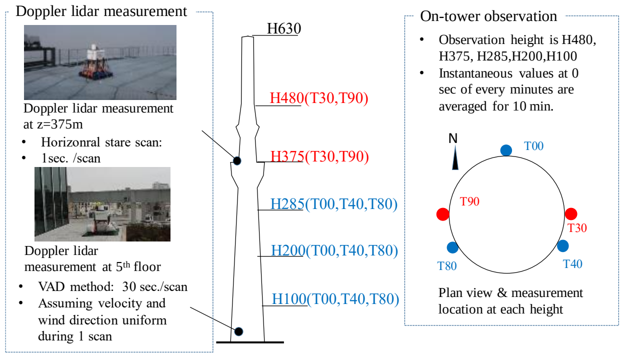


Figure 3. Set up of lidar around high tower.

Table.1 Specification of Doppler lidar at high tower.

System	Halo Photonics streamline XR
Size	63x53x40
Scanning Wavelength	1.55μm
Resolution	30m
Velocity range	±38.0m/s
Scanning mode	VAD(Vertical Azimuth Display): Mar.16-Apr.3 Horizontal Stare Scanning: Apr.3-Apr.20
Output data	Doppler velocity, SNR

FIELD MEASUREMENT FOR WIND

Outline of Field Measurement

Observation by Doppler lidar is carried out in Tokyo city area which is located 9km away from coastal area in order to observe the characteristics in vertical profile of velocity.

Figure 3 shows set up of lidar around high-rise tower and table 1 shows the specification of Doppler lidar. For observation, VAD (Vertical Azimuth Display) method is employed and velocity data in the height of 0-1900m from ground are obtained at the interval of approximately 30 seconds.

The Doppler lidar observation was carried out close to the high-rise tower located 9km far from coastal area in order to estimate the statistical characteristics in vertical velocity profile. Observational period is March 16 –April 19 of 2018, and strong wind from south is expected due to strong cyclone in spring season. At the same time wind velocity is measured using propeller-vane anemometer installed at several heights on the tower.

Figure 4 demonstrates comparison of the profiles on averaged and fluctuating components of streamwise velocity between both of the on-site measurements by propeller vane anemometer (provided by the owner of tower) and Doppler lidar. The purpose of this validation is based on the fact that the time resolution of Doppler lidar is coarser than the time resolution of on-tower anemometer measurement. There is small difference in standard deviations (SD) obtained by two manners as shown in figure 4. Figure 4 also shows a good agreement between the two time-averaged velocity profiles.

NUMERICAL PREDICTION BY BCM-LES BASED ON SPATIALLY DEVELOPING TURBULENT BOUNDARY LAYER

Numerical Model and Conditions

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 (Figure 5). Calculation grid number by BCM is approximately 60 million.

The sizes of the computational domain are 12.8km x 3.2km x 3.2km. With these computational domains, the finest resolution is determined as 6.25 meter with 16x16x16 cells in each Cartesian mesh . The TOKYO urban geometry is generated by GIS data of topography and buildings. The numerical method and calculation condition is shown in Table 2. A turbulent inflow condition is imposed to inlet surface. For inflow condition, turbulent boundary layer which is generated by driver region simulation with semi-periodical boundary condition (Lund et al., 1998) is imposed.

Validation of LES in Comparison with Observational Data

Figure 6 shows vertical profile of average velocity $U(z)$ and turbulent intensity $\sigma(z)/U(z)$ which is obtained by CFD and Doppler lidar observation at the observation point. Vertical profile of average velocity in CFD show the tendency corresponding to power law over the height of 400m from ground and also results of observation data show same tendency. For rms value of velocity, in the height less than 200m where the effect of urban canopy is dominant, the turbulent intensities $\sigma(z)/U(z)$ obtained from CFD and observation are corresponded well. However upper region higher than 200m height, the results of CFD is underestimated in comparison with that of observation data because observation data includes weather disturbance fluctuating at the smaller frequency.

Basic Wind Profiles and Occurrence of Maximum Peaks of Velocity Fluctuation in Urban Area

As depicted in Figure 7, the time-averaged ($\langle u \rangle$), SD (σ_u), and instantaneous velocity (u) contours on the xz plane obtained by BCM-LES show a process of the development of turbulent boundary layer over urban surface.

Figure 8 shows the peak wind velocity contours in the vertical plane which are related to the strong wind disaster. Four areas with high maximum velocity peak are recognized locally above low-rise buildings based on LES data. Actually, due to the short duration of simulation time, these peaks occur within the limited range. But if the simulation time is long enough, it is expected that the velocity peak will be distributed in a longer spatial range. Interestingly, it can be observed that there are some different low-peak occurrences, which locally appear within the red circle areas depicted in the figure of color contours. In each area five vertical lines are set in order to show quantitatively instantaneous maximum wind speed with the time-

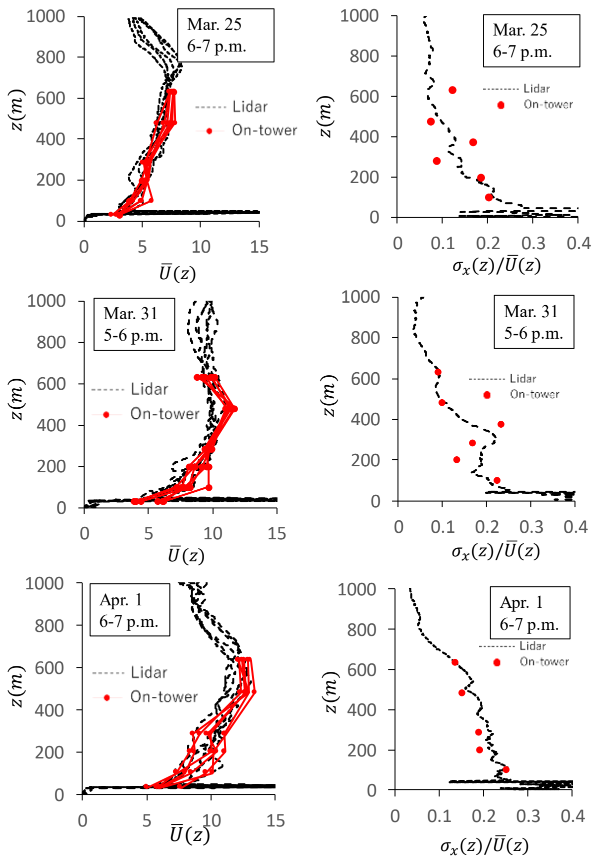


Figure 4. Field measurement data of wind.
Mean wind velocity Turbulent intensity

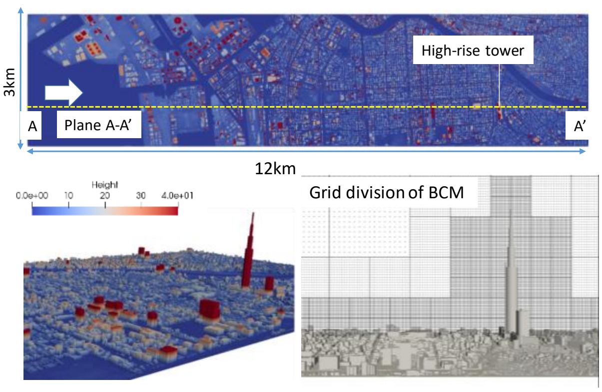


Figure 5. Numerical model for urban area.

Table 2. Numerical method and conditions.

Re	$U_\infty\delta/\nu = 2.304 \times 10^7$
Resolution	$\Delta t U_\infty/\delta = 0.00129$, 6.25m (Minimum)
Time integration	2nd order Crank-Nicolson
Spatial discretization	Convective term:2nd order Central+5% Upwind Diffusion term：2nd order Central
Boundary condition	Wall：No-slip type IBM Side,Top：Slip Inlet：inflow turbulence ($\alpha = 1/7$, δ=400[m], Re_τ=590) Outflow：convective

averaged, fluctuating and peak maximum velocities. For capturing the correlation between the peak locations and roughness parameters such as average height of building, the ensemble average profiles at four observational areas are produced based on five vertical profiles. The height where the maximum occurs is located at approximately three times of the average height of

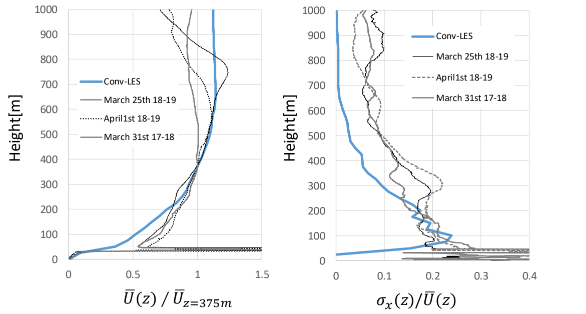


Figure 6. Numerical validation comparing with field measurement data.

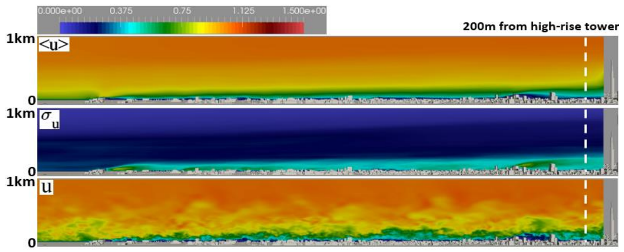


Figure 7. Numerical results of developing turbulent boundary layer over Tokyo.

the buildings and lower than the peak location of fluctuating velocity. According to various roughness parameters, reasonable profile is numerically obtained for the time averaged velocity in four areas.

As also shown in Figure 9, the instantaneous maximum peaks of fluctuating velocity as a function of reference height normalized by average height at four observational areas are focused. As can be seen from the figures of vertical peak fluctuation profile the instantaneous velocity peaks are scattered from 0.25 to 0.45 (30% of mean streamwise velocity $\langle u \rangle$) for five vertical profiles at each observational location. That might be due to the heterogeneous effect in which the realistic buildings are arranged in locally sparse or dense areas. Variation of peak fluctuation in the vertical direction has sometimes maintained their shape as a result of the convective behavior of peak values.

ENVIEONMENTAL TURBULENCE IN URBAN BOUNDARY LAYER WITH METEOROLOGICAL DISTURBANCE

Making inflow including meteorological disturbance

This chapter reveals the effect of meteorological disturbance on turbulent field of urban boundary layer using inflow condition with meteorological disturbance. First, the time series data of velocity is generated by mesoscale meteorological model, WRF-

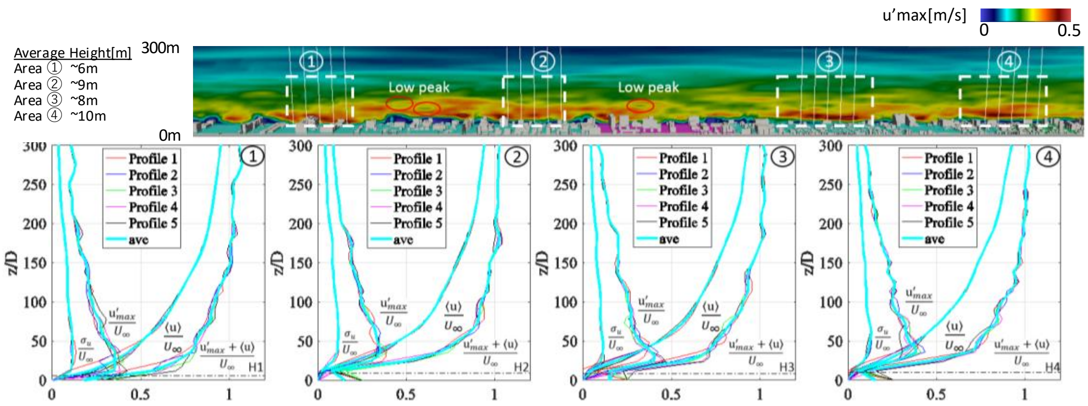


Figure 8. Normalized SD profile; Normalized maximum peak profile; Normalized time-averaged profiles; and normalized profile of summation of maximum peak and time-averaged streamwise velocity.

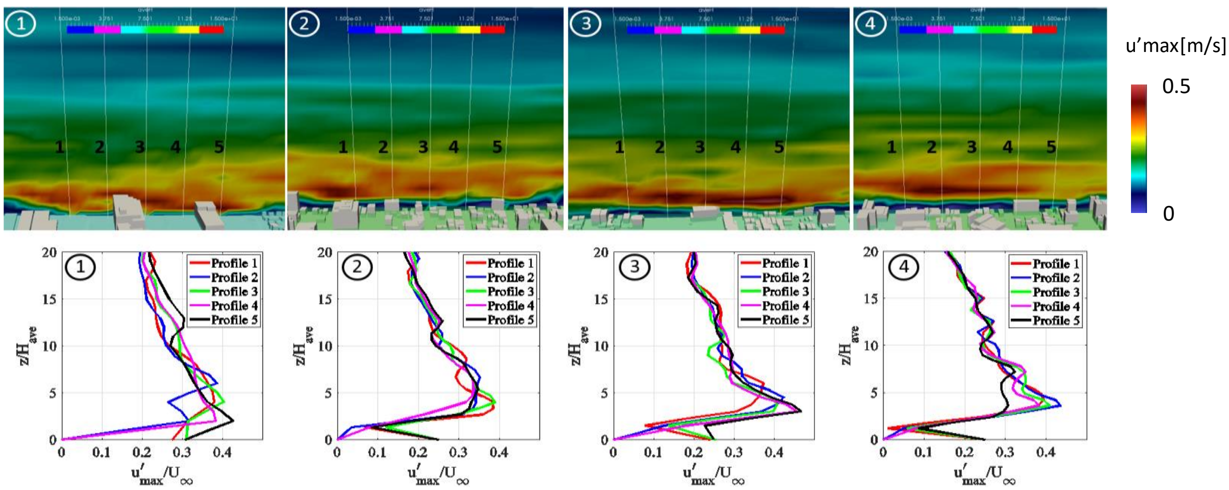


Figure 9. Normalized instantaneous maximum velocity peaks by average height at four observational areas.

LES. In the simulation, One-way nesting of 2 domain (19.5kmx9.5km、13.0kmx6.5km) is employed. Table 3 shows the calculation condition. In general, it is difficult for the meteorological model to high-frequency component of velocity. So, this study applies the method for adding the high-frequency component (Kawai and Tamura, 2015) to the results obtained from WRF-LES. In this method, the fluctuation with high frequency which is generated in the driver region with semi-periodic boundary condition is decomposed physically to the scale of original inflow and residual fluctuation. Then, the residual fluctuation is rescaled and imposed to inlet plane at an appropriate scale of fluctuation (Figure 10).

Figure 11 shows the comparison of turbulent inflow between turbulent boundary layer by the method of Lund et .al and urban boundary layer with meteorological disturbance(UBL). Focusing on the turbulence intensity of each component, the fluctuation of UBL with meteorological disturbance becomes large until the height of 800m because the effect of vertical mixing is strong in the UBL case. Also, the vertical profile of velocity higher than the height of 100m becomes constant. As a result, the vertical profile of velocity in UBL corresponds to power index shown in category II of AIJ recommendation, but the region of velocity deficit is smaller than that in TBL by the method of Lund et.al.

Effect of meteorological disturbance on turbulent field of urban boundary layer

This study carries out BCM-LES using inflow data of UBL with meteorological disturbance (Met-LES). In order to show the effect of meteorological disturbance, the results of Met-LES are compared with those in the results of BCM-LES using inflow data of conventional turbulent boundary layer which is generated by the method of Lund et. al (Conv-LES).

Figure 12 shows the distribution of turbulence intensity on xz plane in both case. In Met-LES, turbulence in upper region (over 500m of height) of inflow is maintained also in the area around high-rise tower while the turbulence intensity of Conv-LES over 500m of height is almost zero.

Figure 13 shows numerical validation of TBL and UBL with meteorological disturbance. The averaged velocity of both shows good agreements except the region less than height of 200m, which is affected by the heterogeneity of urban canopy.

Table 3. Calculation condition of WRF-LES

Time increment		1/3s (Domain1), 1/12s (Domain2)
Spatial resolution		Horizontal: 100m (Domain1), 25m (Domain2) Vertical: 15m(Almost uniform)
Surface layer scheme		Revised MM5 scheme (Jimenez et. al 2011)
SGS model		1.5 order TKE closure (3D)
Boundary condition	Inflow /outflow	Periodic
	Side	Periodic
	Bottom	Surface layer scheme , heat flux=0

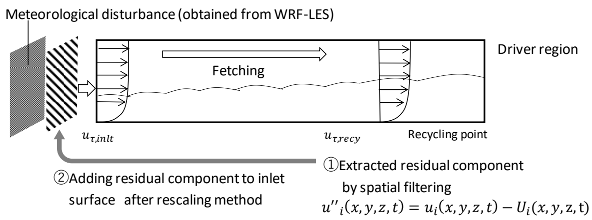
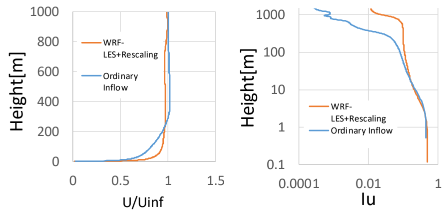
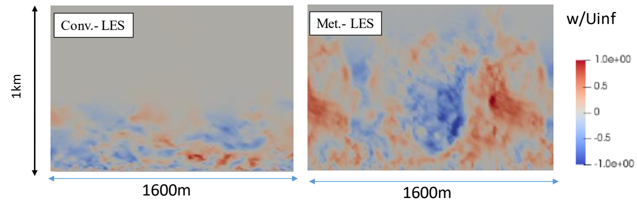


Figure 10. Numerical model for inflow turbulence with meteorological disturbance.



(a) Inflow condition: Vertical profile of velocity



(b)Inflow condition: w'/Uinf on yz plane

Figure 11. Inflow turbulence structures of TBL and UBL with meteorological disturbance.

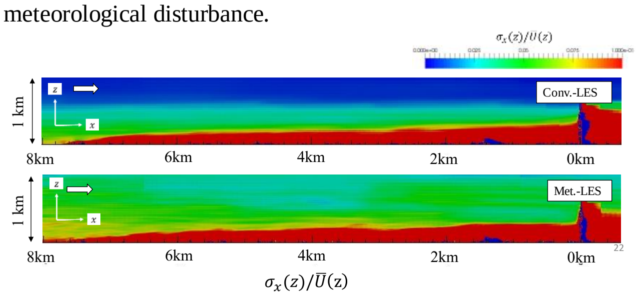


Figure 12. Numerical results of wind velocity distribution for developing TBL and UBL with meteorological disturbance.

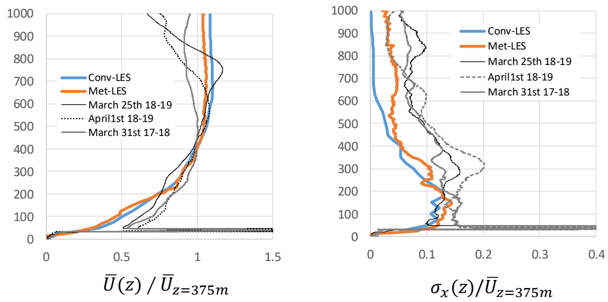


Figure 13 Numerical validation of TBL and UBL with meteorological disturbance.

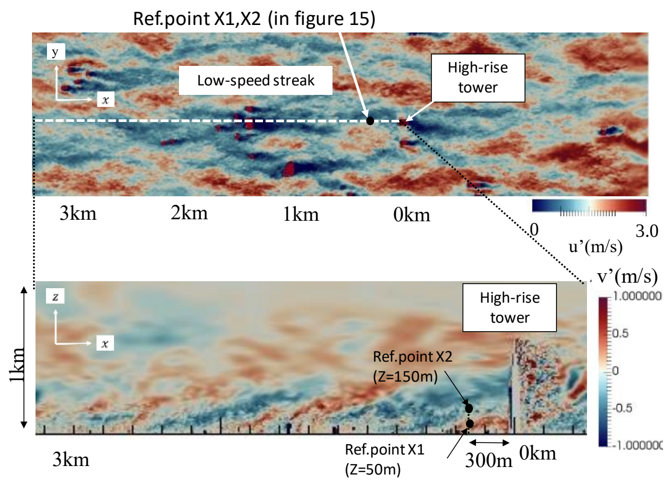


Figure 14. Turbulent structures above and within urban canopy for developing UBL with meteorological disturbance.

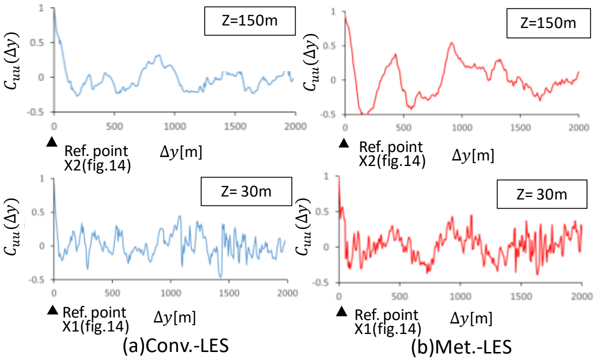


Figure 15. Spatial correlation of wind velocity above and within urban canopy for developing UBL with meteorological disturbance.

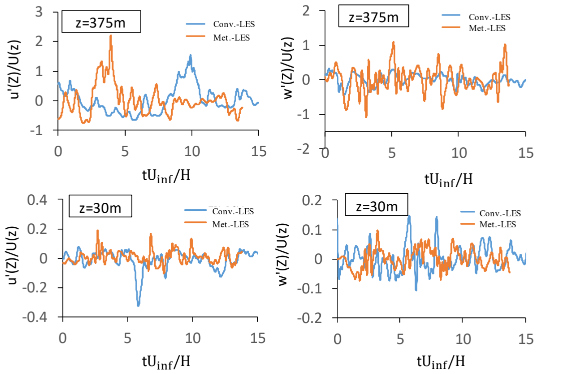


Figure 16. Numerical results of time history of turbulent wind for developing TBL and UBL with meteorological disturbance.

Next, focusing on the turbulence structure in UBL, figure 14 shows turbulent structures above and within urban canopy for developing UBL with meteorological disturbance. At the height of 60m, In Met-LES, large scale of streaky structure appears and its interval is almost around 500m. Then, focusing on xz plane of v', upward inclined structure extends to the height of 500m.

Figure 15 shows spatial correlation of wind velocity above and within urban canopy for developing UBL with meteorological disturbance. Spatial correlation is calculated by the equations (1), (2) .

$$u'(x,y,z) = u(x,y,z)\text{-}\langle u\rangle(x,y,z) \quad (1)$$

$$C_{uu}(\Delta y) = \frac{\frac{1}{T}\int_0^T u'(x_0,y_0+\Delta y,z_0)\, u'(x_0,y_0,z_0)dt}{\sigma(x_0,y_0+\Delta y,z_0)\sigma(x_0,y_0,z_0)} \quad (2)$$

where x_0, y_0, z_0 are Coordinate of reference point (shown in figure 14), u' is fluctuation of velocity, $\langle u\rangle$ is time average of velocity, σ is standard deviation of velocity.

In both cases of Conv.-LES and Met.-LES, the spatial frequency of correlation is larger at the lower height. On the other hand, the low frequency of fluctuation appears above the urban canopy. However, In Met.-LES, low frequency of fluctuation appears in addition to high frequency fluctuation.

Figure 16 shows the time history of turbulent wind for developing TBL and UBL with meteorological disturbance.

At the height of 375m, the fluctuation of u' in Met-LES become larger than that of Conv.-LES. Also, the fluctuation of u' at the height of 30m shows the intermittent peak value. The results imply that the large scale of fluctuation which is derived from meteorological disturbance in upper area of UBL affects the characteristics of fluctuation of u in surface layer.

CONCLUSIONS

This paper discussed the environmental turbulence above the urban area based on the field measurement and LES data. Tokyo is the research object as a very large city. Numerical simulation by the BCM-LES and field observation using lidar were performed so as to reveal several interesting features of wind in turbulent boundary layer over TOKYO area. LES model using BCM was validated by using the field measurement data.

Vertical wind velocity profiles for time-averaged, fluctuating and peak components were elucidated relating with roughness patterns at urban area. Also, various kind of coherent structures of turbulence were investigated above and within urban canopies. For safety of buildings and structures on the urban area, wind gust related to instantaneous velocity peak within urban region is investigated. As inflow turbulence, urban boundary layer with meteorological disturbance as well as conventional turbulent boundary layer is employed. The occurrence of instantaneous velocity peak was recognized above the within the urban canopy where the peak location is approximately three times of average building height. Finally, due to the heterogeneous effect, it is clarified that instantaneous velocity peaks reaches at approximately 30% of the mean streamwise velocity.

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