LES on wind pressure acting on high-rise building under strong wind events of Typhoon

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Abstract. *This study predicts wind pressure on high-rise buildings under typhoons by LES using CUBE and discuss the effects of turbulence fields obtained from broad region simulation and fine vortex structure around complicated facade on wind pressure. First, the computation of broad region including many high-rise building is carried out. The computation reveals that structures with streamwise vorticity appears from the upper corner of high-rise building and remains even in 1km leeward region. Then, the computation resolving the complicated façade of two buildings is carried out and turbulent structure around the complicated façade is examined. The result shows that it is possible to show local wind pressure induced by fine structure of vortex by the computation with high spatial resolution resolving the shape of unevenness on building façade.*

1 INTRODUCTION

In recent years, extremely large typhoons have frequently hit large cities, causing numerous exterior damages to buildings. These damages are mainly caused by wind pressure acting on the building members locally. To enhance the performance on wind resistance against such frequent typhoons, it is necessary to predict the wind pressure acting on buildings by wind tunnel experiments and CFD.

On the other hand, the progress of calculation technology based on HPC has been remarkable in recent years, and wind-resistant design using LES is becoming more practical. In particular, computation with the grid number of several hundred million to one billion have becomes possible by using supercomputer. In addition, the use of hierarchical Cartesian grid such as CUBE (developed by RIKEN R-CCS) [1] makes the load balance equal, and high parallel

performance is expected even for LES with a large number of grids. Also, the introduction of IBM-based boundary conditions makes it possible to reproduce turbulent flow fields around complicated shapes such as cities and detailed configuration of buildings. With these advances in techniques, it is expected to reveal the effects of wake turbulence on windward building and meteorological disturbance with large scale of fluctuation by broad region computation, and to confirm small-scale turbulent structures around complex exterior materials based on high-resolution computation. In particular, turbulent fluctuations with large scales, such as meteorological fields, and eddies generated by nearby high-rise buildings causes unsteady wind pressure fluctuations on buildings. Fine eddies generated from complicated form of building facades can also generate extreme wind pressure locally.

This study predicts wind pressure on high-rise buildings under typhoons by LES using CUBE (developed by RIKEN R-CCS) [1] and discuss the effects of turbulence fields obtained from broad region simulation and fine vortex structure around complicated facade on wind pressure.

2 MAKING INFLOW CONDITION

2.1 Outline for making inflow condition

This study carries out the simulation for 9km x 9km region of Tokyo central area using BCM (Building Cube Method) . Simulation code is CUBE developed by RIKEN (Jansson et al. 2018). Spatial resolution is 2.25m, and calculation grid number is approximately 960 million. For inflow condition, two type of inflow condition is imposed to boundary condition of calculation domain. One is turbulent boundary layer (TBL), and the other is inflow condition including meteorological fluctuation, which is generated by adding high-frequency component to results of meteorological model (WRF-LES) (figure 1). In this study, inflow database of velocity is extracted at sampling plane (location is shown in figure 2). for broad region analysis. The extracted inflow database is used for inflow condition of more finer calculation domain including actual target building and the wind pressure on target building considering roughness condition of actual urban area and meteorological fluctuation is estimated. For inflow condition for broad region simulation, 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)[2].

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[3]. 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)[4]. 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.

The figure 3 shows vertical profile of velocity and power spectrum. In the generated inflow condition, velocity with high frequency fluctuation is generated and turbulent intensity increases near ground region (z <1000m) compared with original WRF-LES results.
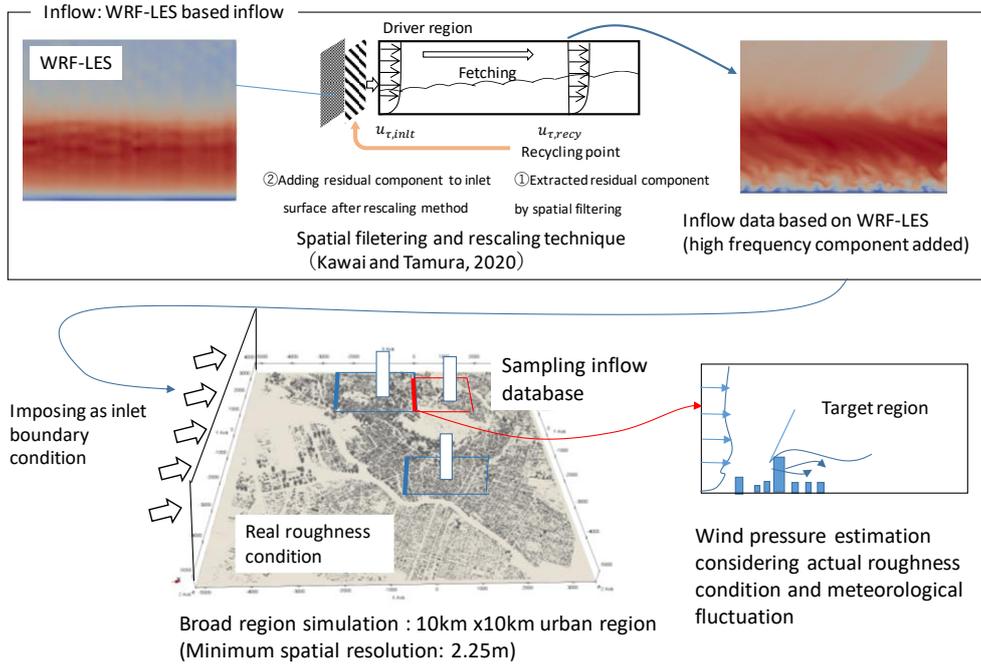
Figure 1 : Outline for making inflow condition

(a) Calculation domain   (b)Grid division (Red line: Cube, Black line :Grid）
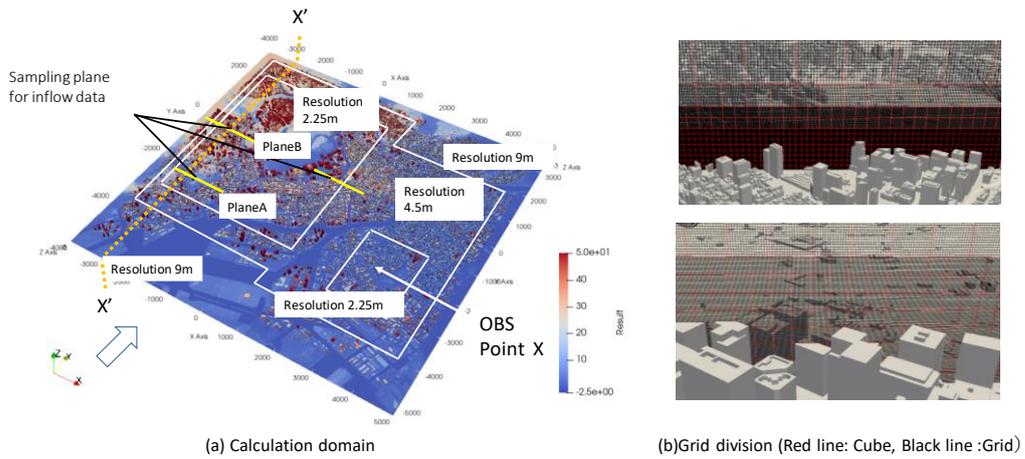
Figure 2: Calculation domain and grid

(a) Vertical profile of u

(b) Power spectrum of u
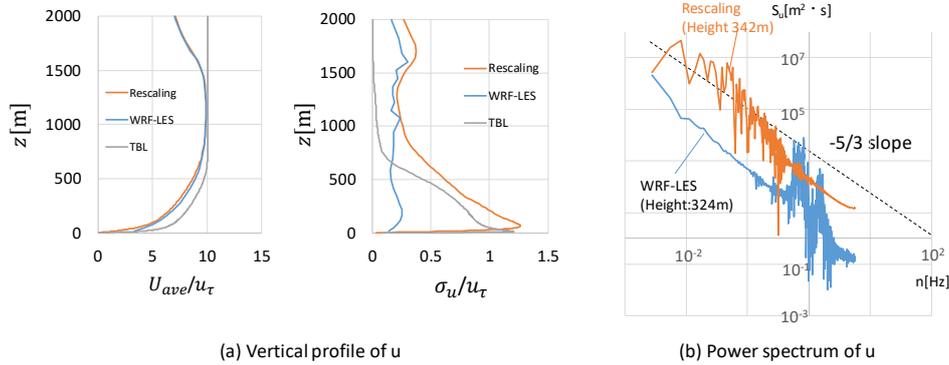
Figure 3 : Inflow condition for broad region analysis

2.3 Result of broad region simulation (9kmx9km domain)

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 2(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 figure 4, large u_{rms} value remains in upper height of boundary layer around 1000m height in the case of WRF-LES based inflow condition.
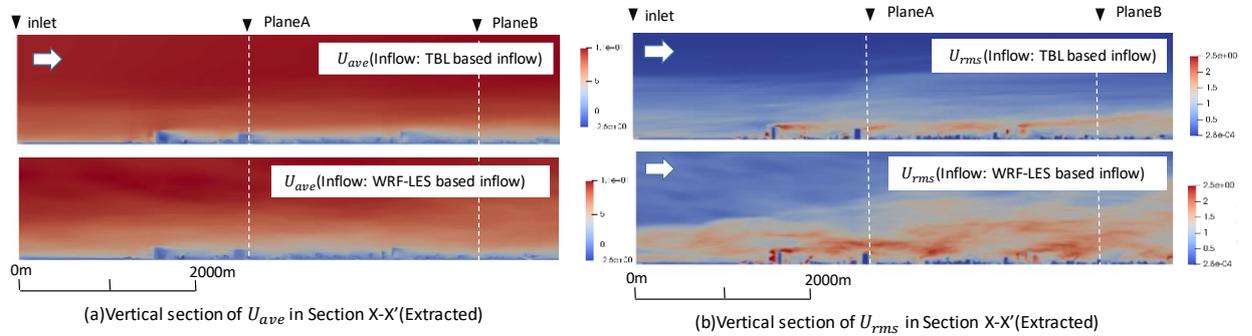

(a)Vertical section of U_{ave} in Section X-X'(Extracted)

(b)Vertical section of U_{rms} in Section X-X'(Extracted)

Figure 4 Vertical section of Uave and Urms

2.4 Turbulence characteristics of extracted inflow data

Figure 5 shows extracted inflow database of velocity (u,v,w) in PlaneB. The extracted velocity database 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 atomospheric 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 6 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.
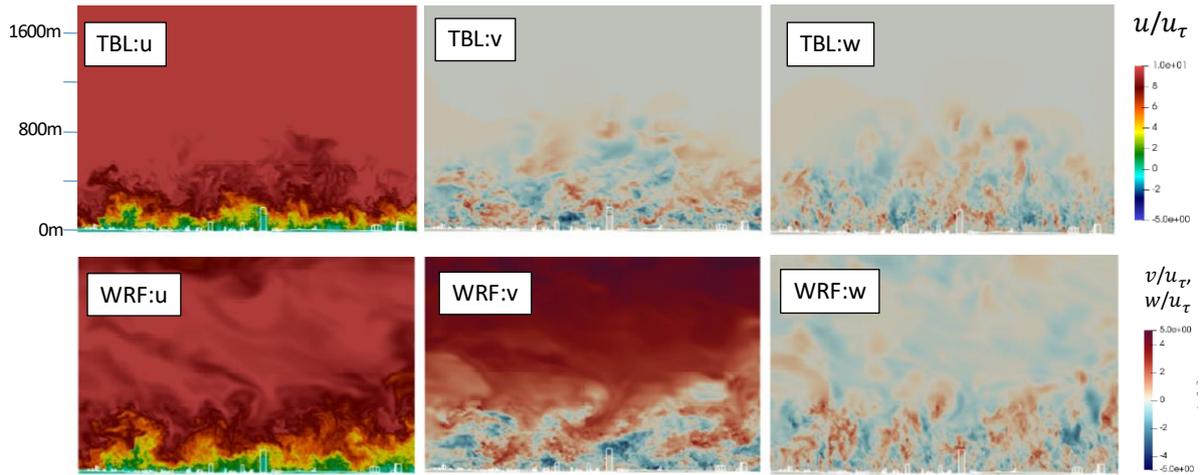

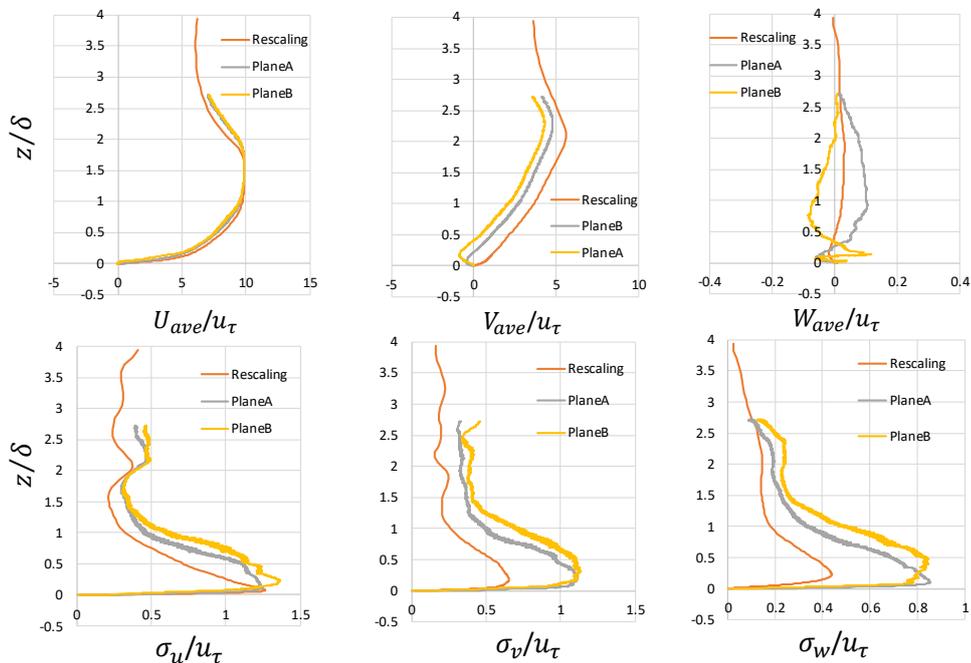**Figure 5** Extracted inflow database of velocity (u,v,w)

Figure 6 : Vertical profile of velocity in sampling planes (WRF-LES based inflow condition)

5

3 EFFECT OF TURBULENT FIELD OBTAINED FROM BROAD REGION SIMULATION ON WIND PRESSURE ESTIMATION

In ordinary model for estimation of wind pressure in wind tunnel experiment and CFD, shape of surrounding building and terrain is reproduced in the area within a radius of 300~400m from target building. However, it is possible to reproduce shape in more broad region by high performance computing recently. In the center area of Tokyo, many high-rise buildings are located sparsely. Generally speaking, the effect of wake turbulence of windward building remains in 1km leeward region, which is equivalent to ten times of building height. This study examines the effect of wake turbulence from several buildings which is away from target building with a distance beyond 500m.

3.1 Calculation condition

Target site is located inside broad region domain (9km x 9km) of Tokyo central area as shown in previous section. The calculation domain reproduces building and terrain within radius of 1.2 km from target area (Fig. 7). Height of target building is approximately 330m. Target site has many high-rise building over 150m. Minimum of spatial resolution is 1.37m and total mesh number is 0.4 billion.

Figure 7: Target area

3.2 Simulation result

Figure 8 shows occurrence of large negative pressure (Isosurface of Cp =-0.8). Isosurface shows large negative pressure occurs leeward corner of building. In particular, negative pressure becomes strong at the height of approximately 250m because vortices generated from rooftop of building A approaches to the leeward corner of target building. The vortices generated from rooftop of building A are also affected from shear layer of windward buildings.

Figure 9 shows Instantaneous velocity u and vorticity z field at the height of 150m, 200m, and 250m. Vorticity field (x component) shows separation shear layer from building A and B approaches wall of target building and these shear layer affect unsteady change of wind pressure on target building. However, in this case, behavior of shear layer from building A and B is affected from building C, D , E, and F which is 1000m windward of target building A. Also, vortex structure from separation of windward buildings are transported to upper area. In the vorticity field at 250m height, vortex structure derives from buildings C,D,E, whose building

6

height are 150-200m.

In addition, figure 10 shows isosurface of absolute value of vorticity x ($|\omega x|=0.3$) colored by vorticity x. In the region above 150m, turbulence with high vorticity appears from high-rise building. The figure implies that fine turbulent structure approaches to leeward high-rise buildings. In the ordinary computation using turbulent boundary inflow condition, it is impossible to reproduce these fine turbulence structure. In the estimation of wind pressure on the building locating in urban area with high-rise building clusters as the central area of Tokyo, the effect of these turbulence structure should be clarified.
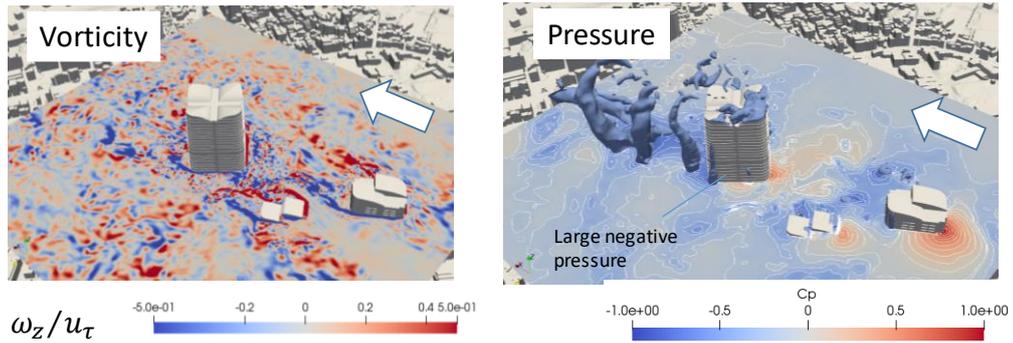

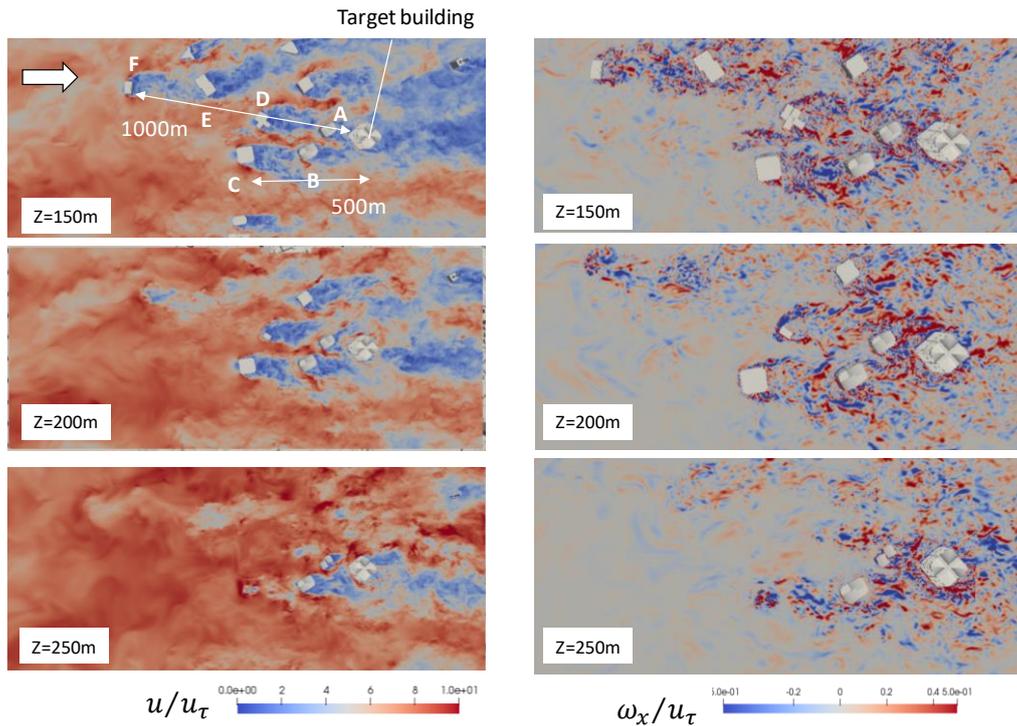**Figure 8**: Occurrence of large negative pressure (Horizontal plane: z=250m)

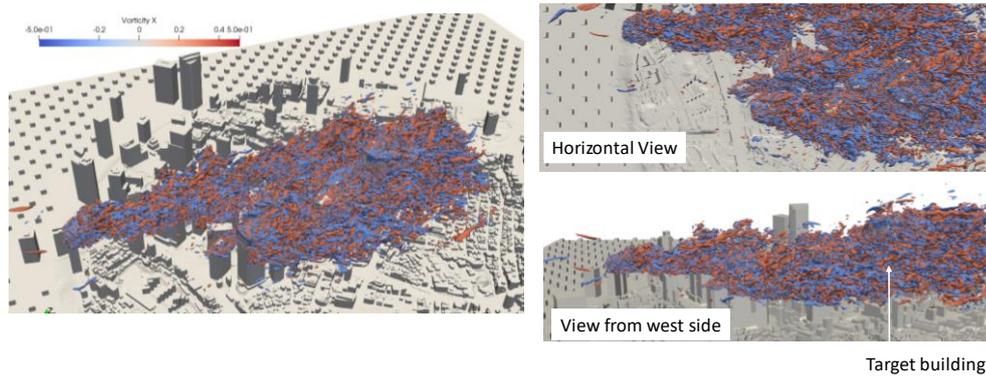**Figure 9**: Instantaneous velocity u and vorticity z field at the height of 150m,200m,and 250m

7

Figure 10: Isosurface of absolute value of vorticity x (|ωx|=0.3) colored by vorticity x

4   TURBULENT STRUCTURE AROUND COMPLICATED SHAPE OF FAÇADE

In the ordinary estimation of wind pressure on building, volume of building is reproduced, and the complicated shape of façade including shading devices and vertical fin is rarely reproduced. These complicated shape is considered sometimes, but it is difficult to reproduce the detailed shape of façade with several ten cm scale at actual scale in CFD and experiment model because of limitation of experiment model scale or grid resolution.

In this chapter, turbulent structure around complicated shape of façade is clarified and its effect on wind pressure of building is discussed.

4.1 Calculation condition

Target site including two target buildings (a),(b) is located in 9km x 9km region of Tokyo central area. In building (a), many pillars and beams which exist away from external wall makes shape of façade complicated. In building (b), solar shading device with uneven shape is installed on the wall of lower part. Also horizontal and vertical groove exists between shading device. The calculation domain reproduces building and terrain in the region 600m away from target building. Minimum of spatial resolution is 0.25m and total mesh number is 0.5 billion. In the target buildings (a),(b) several 10cm scale of shape in façade are reproduced (Figure 11). Also, the inflow database extracted in Plane B are imposed to inlet plane of calculation domain.

4.2 Simulation results

Figures 12, 13 show comparison of turbulent field with the case by 0.5m spatial resolution (Kondo et al.[5]). In building (a), many pillars and beams which exist away from external wall makes shape of façade complicated. This computation using 0.25m spatial resolution resolves complicated flow which passes between small pillar shapes clearly compared with the case of 0.5m resolution. Also, fine vortex structure generates from corner of high-rise building in figure 14. In building (b), finer structure of turbulence appears clearly from shading device with uneven shape.

Figure 15 shows isosurface of q-criterion and streamline passing on building facade as vortex structure generated from complicated shape of façade in building (b). In the figure of iso-surface of q-criterion, vortex structure doesn't appear in the upper part of wall without shading device. On the other hand, many small vortex appears from lower part of wall with shading device. In

8

addition, in building (b), horizontal groove exists between shading device. Near the horizontal groove elongated structure appears and the structure surrounds the corner of building. The structure is induced by circulating flow in the groove. The streamline in figure 15 shows that upper flow goes down from stagnation point and goes into the groove. The flow inside the groove passes toward the corner of building with generating vortex with spiral rotation.

These result shows that it is possible to show local wind pressure induced by fine structure of vortex by the computation with high spatial resolution resolving the shape of unevenness on building façade.
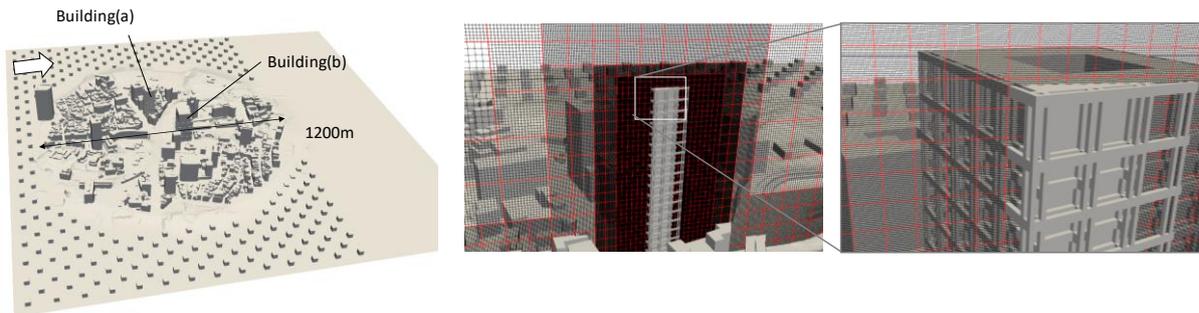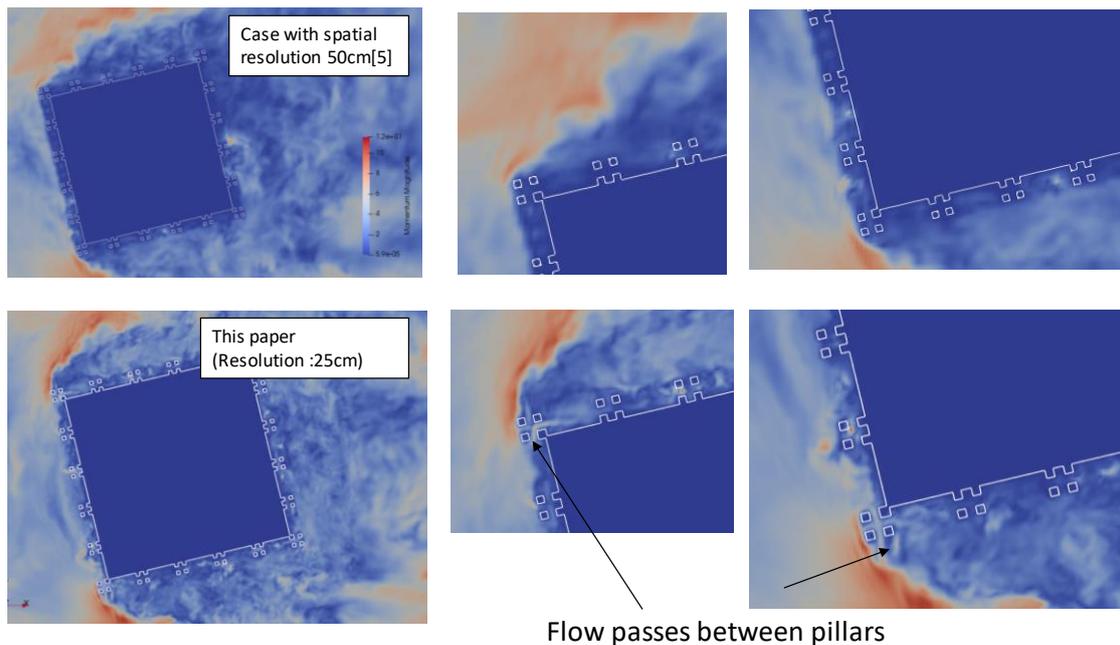

Figure 11 : Target area and grid division

Flow passes between pillars

Figure 12 : Comparison of turbulent field (H=100m)with the case by 0.5m spatial resolution (Kondo et al.[5]). (Building A)
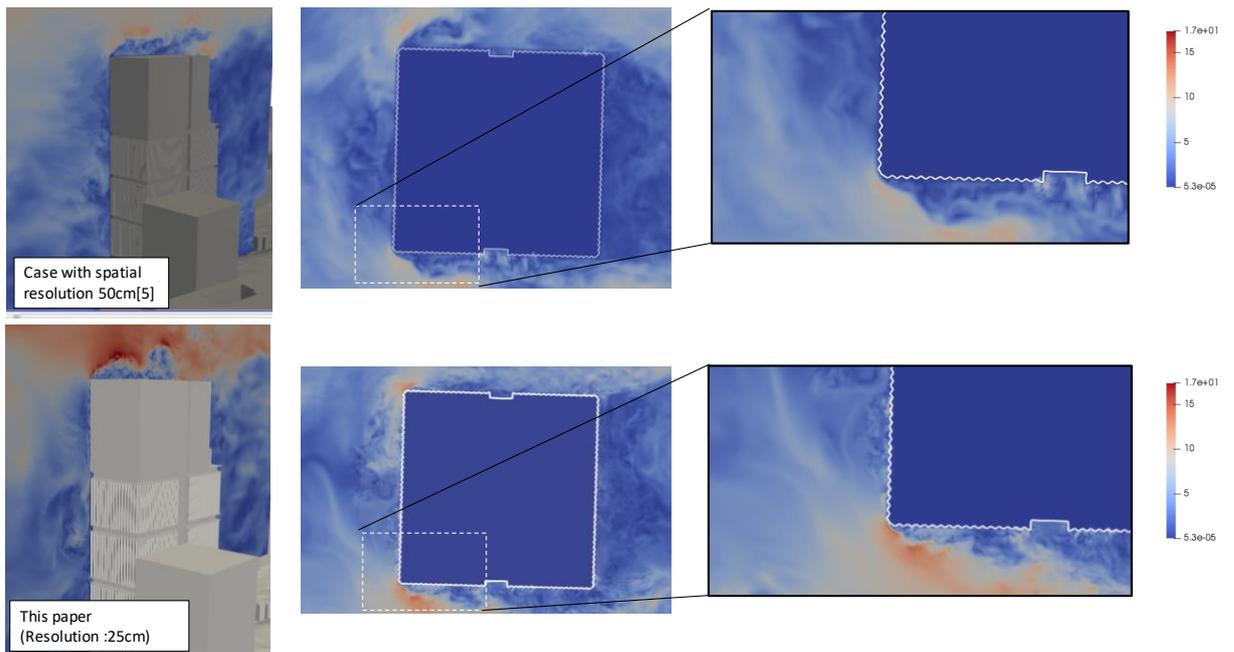
9

Figure 13 : Comparison of turbulent field with the case by 0.5m spatial resolution
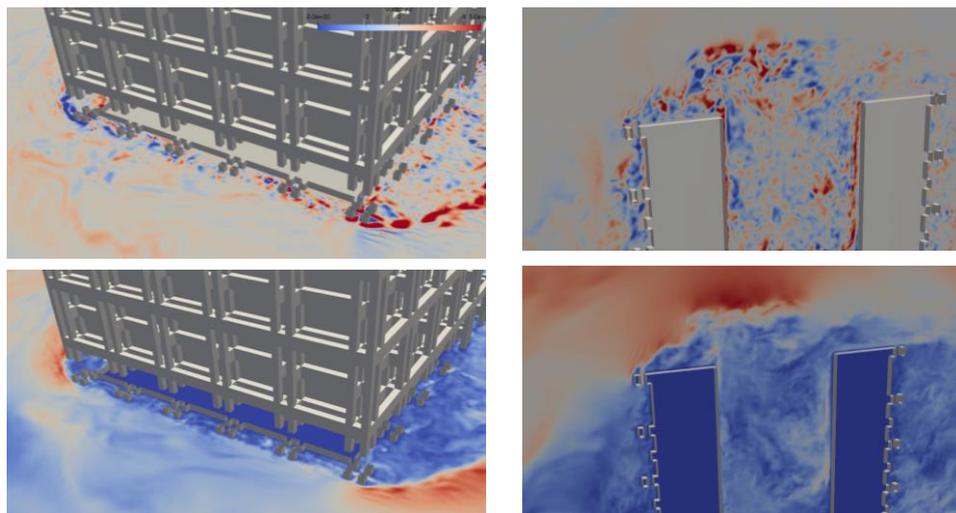(Kondo et al.[5]). (Building B)

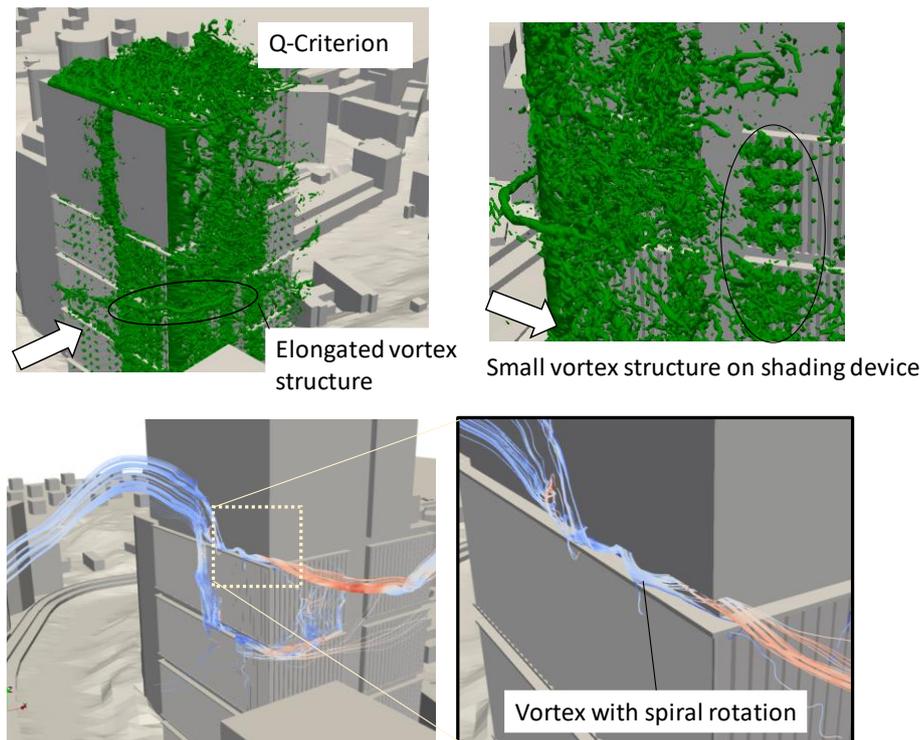**Figure 14** : Vorticity (z component) and velocity filed around building A

Figure 15 : Vortex structure generated from complicated shape of façade

5 CONCLUSIONS

This study predicted wind pressure on high-rise buildings under typhoons by LES using CUBE and discussed the effects of turbulence fields obtained from broad region simulation and fine vortex structure around complicated facade on wind pressure.

First, the computation of broad region including many high-rise building is carried out. The computation reveals that structures with streamwise vorticity appears from the upper corner of high-rise building and remains even in 1km leeward region. These results imply that the effect of these turbulence structure should be clarified by the computation including broad region in the estimation of wind pressure on the building in urban area with high-rise building clusters as the central area of Tokyo.

Then, the computation resolving the complicated façade of two buildings is carried out and turbulent structure around the complicated façade is examined. The result shows that it is possible to show local wind pressure induced by fine structure of vortex by the computation with high spatial resolution resolving the shape of unevenness on building façade.

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