Sixth International Symposium on Turbulence and Shear Flow Phenomena
Seoul, Korea, 22-24 June 2009

LARGE EDDY SIMULATION OF WIND TURBULENCE IN ACTUAL URBAN ENVIRONMENT

Tetsuro Tamura
Department of Environmental Science and Technology,
Tokyo Institute of Technology
4259 Nagatsuta, Yokohama, 226-8502, Japan
tamura@depe.titech.ac.jp

Takeshi Kishida
Wind Engineering Institute
3-29 Kandajinbo-cho, Chiyoda-ku, Tokyo, 101-0051, Japan
kishida@wei.co.jp

Yasuo Okuda
Building Research Institute
1 Tachihara, Tsukuba, 305-0802, Japan
y_okuda@kenken.go.jp

ABSTRACT

In order to establish a sophisticated numerical model for urban atmospheric environment by applying large eddy simulation (LES) technique to wind flows and their turbulence within a city, this study investigates the technological potential and the future trend of LES for employing the computational model which directly represents an actual shape found inside a city, such as buildings, structures, vegetation and various kinds of terrain. A numerical model in an actual urban area has been constructed using GIS (Geophysic Information System) data with high resolution, and the inflow boundary condition has been appropriately given by numerically simulating the turbulence characteristics of natural wind flow. This study has aimed at estimating wind in an actual urban area by combination of LES and MM5 techniques. Also, detailed comparison of LES results with full-scale measurement data has been carried out for the model validation.

INTRODUCTION

For constructing an appropriate numerical model to clarify the urban environment in the atmosphere, such as wind flow characteristics and their turbulence structures within a city, the technological potential and the future development of large eddy simulation (LES) should be examined with regard to the complicated turbulent flows near the various shapes of surfaces. LES has been frequently used for fundamental problems of simple turbulent flows where adequate understandings of physical mechanism are required strongly. Recent advancement of LES technique has made it possible to give a feasible data in wind engineering (Tamura, 2008a). Especially, we can employ nowadays the computational model which directly expresses an actual and complex configuration at surface of city, such as buildings, structures, vegetation and trees on various kinds of terrain. In spite of such a complicated shape for a city, urban wind flows have been thus far investigated mainly by the model represented using homogeneously-arrayed roughness blocks on the ground. For this situation, some canopy models have been proposed by many researchers, but their effectiveness or availability is ambiguous for the actual urban area. For such a complicated urban aspect, recent advancement of GIS data has made it possible to reproduce a model with actual urban surface aspects (Tamura and Kishida et al., 2009, Kishida and Tamura et al., 2009). We focus on inside the urban canopy where near-ground flows are very complex and unsteady due to flow separation and vortex shedding among building roughness elements. To predict the wind near the ground level, we take into cosideration a necessity for formulation of the numerical model which can traces correctly aspects of the urban surface condition.

Also, detailed comparison of LES results with full-scale measurement data should be carried out for the model validation. Generally, LES cannot evaluate the absolute wind speed on specified date at a specified site. We can get only a value relative to the reference wind speed. In order to introduce the absolute value, the authors proposed an utilization of the mesoscale meteorological model (for example, 5th Generation Mesoscale Model: MM5). That is to say, they showed an evaluation of the absolute values in LES by combining MM5 and LES results at the reference location, such as the internal boundary-layer height (Tamura and Takei et al., 2008b). Accordingly, we can also generate the approaching wind turbulence with evaluating the specific level of wind speed over the actual urban area.

This study has aimed at estimating wind velocity and wind turbulence in an actual urban area by combination of LES and MM5 techniques. As the meteorological event, we consider the high wind during cyclogenesis generated near Japan in January, 2006. We deal with two examples for the

Sixth International Symposium on Turbulence and Shear Flow Phenomena
Seoul, Korea, 22-24 June 2009

urban area in the center of Tokyo, one is around an isolated tall building and the other is an urban canopy area formed by multiple tall buildings. A sophisticated numerical model in an actual urban area has been constructed using GIS data with high resolution, and the inflow boundary condition has been appropriately given by numerically simulating the turbulence characteristics of natural wind flow over the urban area.

PROBLEM FORMULATION

Governing Equations and LES Model

The governing equations consist of the filtered forms of the continuity equation and the Navier-Stokes equation as follows:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$
$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(-\tau_{ij} + 2\nu \overline{S_{ij}}\right)$$
$$\tau_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j, \quad \overline{S_{ij}} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$$
$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = -2\nu_e \overline{S_{ij}}$$
$$\nu_e = (C_S \Delta)^2 (2\overline{S_{ij}}\,\overline{S_{ij}})^{1/2} \qquad (1)$$

where i=1,2,3 correspond to the directions x, y and z, respectively. The summation rule is assumed for repeated indices. u_i, p, t, τ_{ij} and ν denote velocity, pressure, time, the SGS Reynolds stress and molecular viscosity coefficient, respectively. In this study, the boundary-layer type of flows are mainly treated, so we used the Smagorinsky-type of eddy viscosity model for SGS modeling for the SGS Reynolds stresses, where Cs is set to 0.10.

Numerical Method

The numerical algorithm is based on the fractional-step method. The pressure field is obtained by solving the Poisson equation of pressure. For time-advancing, the Adams-Bashforth method is utilized for both of the convection and the viscous terms. The spatial derivatives are numerically approximated by the second-order central difference.

To simulate a rough surface, rectangular blocks are arranged on the surface as roughness elements without any assumptions such as roughness length. A method proposed by Goldstein et al. (1993) is used to impose the no-slip boundary condition at all surfaces of the roughness element. The forcing term is added to the governing momentum equations. The coupling of the external force and the time derivative acceleration term corresponds to the equation for a kind of oscillation system.

The aspect of configuration at the near-ground surface in the actual urban area is also treated in same manner, so the boundary condition at the bottom surface is imposed by the external forcing technique.

Inflow Turbulence

Lund et al. (1998) proposed a technique for simulating the spatially developing boundary layer. The point of this technique is to rescale the velocity field at a downstream station, and re-introduce it as a boundary condition at the inlet, to allow for the calculation of a spatially developing boundary layer in conjunction with pseudo-periodic boundary conditions applied in the streamwise direction. This method was originally proposed for a smooth-wall boundary layer, and then extended by Nozawa and Tamura (2002) to a rough-wall boundary layer. The outline of their methods is shown at next session.

Quasi Periodic Condition. Based on the concept of the quasi periodic condition, the velocities at the inflow boundary are given by rescaling the velocities at the recycle station. A uniform flow with constant velocity is given in the upper area above the boundary layer. First, the velocity at the recycle station is divided into a mean and a fluctuating component. The mean component is estimated by averaging in time and in the spanwise direction. Both components are rescaled following the law of the wall for the inner region and the defect law for the outer region as follows.

$$\begin{cases} U_{inlt} = \gamma U_{recy}\left(y^*_{inlt}\right) \\ u'_{inlt} = \gamma u'_{recy}\left(y^*_{inlt}\right) \\ u^{inn}_{inlt} = U_{inlt} + u'_{inlt} \end{cases}, y^* = y/l_{inn}, \gamma = \frac{u_{\tau(inlt)}}{u_{\tau(recy)}} \qquad (2)$$

$$\begin{cases} \left(U_\infty - U\right)_{inlt} = \gamma\left(U_\infty - U\right)_{recy}\left(\eta_{inlt}\right) \\ u'_{inlt} = \gamma u'_{recy}\left(\eta_{inlt}\right) \\ u^{out}_{inlt} = U_{inlt} + u'_{inlt} \end{cases}, \eta = \frac{y}{l_{out}} \qquad (3)$$

where l_{inn} and l_{out} are characteristic lengths of the inner and outer regions. The boundary layer thickness δ is used for l_{out}. For l_{inn} wall unit ν/u_τ(u_τ: friction velocity) is given for the smooth surface and equivalent sand roughness height k_s is given for the rough surface. Here, subscripts "*inlt"* and "*recy"* denote physical quantities at inflow and recycle station, respectively. The vertical velocity v and the spanwise velocity w are calculated for γ=1. The computed velocities of the inner and outer regions at the inlet are summed up using the appropriate weighting function.

In order to rescale the velocities, it is necessary to determine the ratio of friction velocity γ and the ratio of boundary layer thickness $\delta_{inlt}/\delta_{recy}$ or alternatively, the ratio of momentum thickness θ because boundary layer thickness cannot be obtained stably from the calculated results. This is based on the assumption that the ratio of δ and θ is constant for the relatively short developing distance in the streamwise direction. For a specified θ_{inlt}, the ratio of momentum thickness β (=$\theta_{inlt}/\theta_{recy}$) can be obtained by calculating θ_{recy} for the rescale process. As for the ratio of friction velocity γ, the relation between β and γ is introduced by using the experimental rules provided by Prandtl et al. (Schlichting, 1979) between the fetch x_a (the distance from the leading edge where turbulent boundary layer begins) and the local or total skin frictions for turbulent boundary layer over rough surface.

$$r = \frac{a'_f}{2.87 + 1.58 \log \frac{x_a}{k_s}}, a'_f = 1.72, \quad (4)$$

$$s = \frac{A_f}{1.89 + 1.62 \log \frac{x_a}{k_s}} \quad , A_f = 1.76 \quad (5)$$

$$\gamma = \beta^{-1/n} \quad , n \equiv \frac{1-s}{r/2} \quad (6)$$

COMPARISON OF MM5 RESULTS WITH OBSERVATIONAL DATA

Figure 1 shows the wind data at a higher point of specific locations in Tokyo obtained by MM5 (meso-scale meteorological model) with the observational wind at the top of several high-rise buildings (Tamura and Kishida et al., 2009, Kishida and Tamura et al., 2009, Tamura and Takei et al., 2008b). This study deals with observational data during cyclogenesis generated near Japan in January, 2006. On the whole, the wind directions estimated by MM5 are surely in good agreement with the observational data. For Roppongi, the wind speed estimated by MM5 is almost in good agreement with the observational data. This area has only an isolated high-rise building and is otherwise uniformly covered by medium-rise buildings. The MM5 results at Roppongi were hardly influenced by the urban canopy layer. However, for Ootemachi and Marunouchi, the wind speed estimated by MM5 are relatively larger than those of the observational data. It can be considered that the MM5 results were greatly influenced by the urban canopy layer, so the wind speed by MM5 was greatly overestimated. In the case of the area with densely-arrayed high-rise buildings, the meteorological model has a limitation for the prediction of the wind flows within the urban canopy. So we can say that LES technique is expected for estimation of the local canopy flows.

WIND FLOW AROUND AN ISOLATED TALL BUILDING

Figure 2 illustrates a numerical model for LES at local urban area in Roppongi of Tokyo. In this study, the numerical model consists of two computational regions, one is for the main region of turbulent flow over actual urban area, and the other is a driver region for the auxiliary simulation for generating inflow turbulence for the main region. As mentioned before, to generate inflow turbulence, we employ the modified version by Nozawa and Tamura (2002) for a rough-wall turbulent boundary layer. Table 1 shows the size and the grid numbers of the computational domains for the case of an isolated tall building.

Generally, LES cannot evaluate the absolute wind speed, but only a value relative to the reference wind speed. In order to introduce the absolute wind speed, we utilize the present MM5 results. In order to combine LES data with MM5 data, the reference point for wind must be given in the computational domain. Considering that the observational data at Roppongi show sufficiently good agreement with MM5 results, we developed a method for coupling LES and MM5. Generally, wind velocity measurement data for a rooftop of an isolated tall building are sometimes used as a reference velocity for observational data. However, wind data at the same height upwind of the building is more expected to be unaffected by the building obstacle. Therefore, we determined a reference point 750m upwind of the rooftop of the high-rise building at a height of about 250m. Accordingly, the LES wind velocity at the reference point can be given as a dimensional value by using the predicted absolute value of MM5 at the same height.

Figure 3 illustrates the instantaneous wind flow patterns around an isolated high-rise building. We can recognize the turbulent flow structures with various scaled vortices in the whole computational region, because turbulent boundary layer is imposed at inflow condition. At a height of 100m, we can find a separated shear layer and vortex-shedding around the high-rise building. Near the ground, dominant flows can be seen along the main street.

Figure 4 compares the LES results with the observational data for the time series of wind speed at the rooftop over Roppongi area for ten minutes. We can see that the time history at the rooftop is slightly affected by a building obstacle and shows a slightly larger variation. We can also see a low-frequency fluctuation in the observational data. Mean wind speed, gust factor and turbulence intensity in the table estimated by LES and MM5 are in relatively good agreement with the observational results.

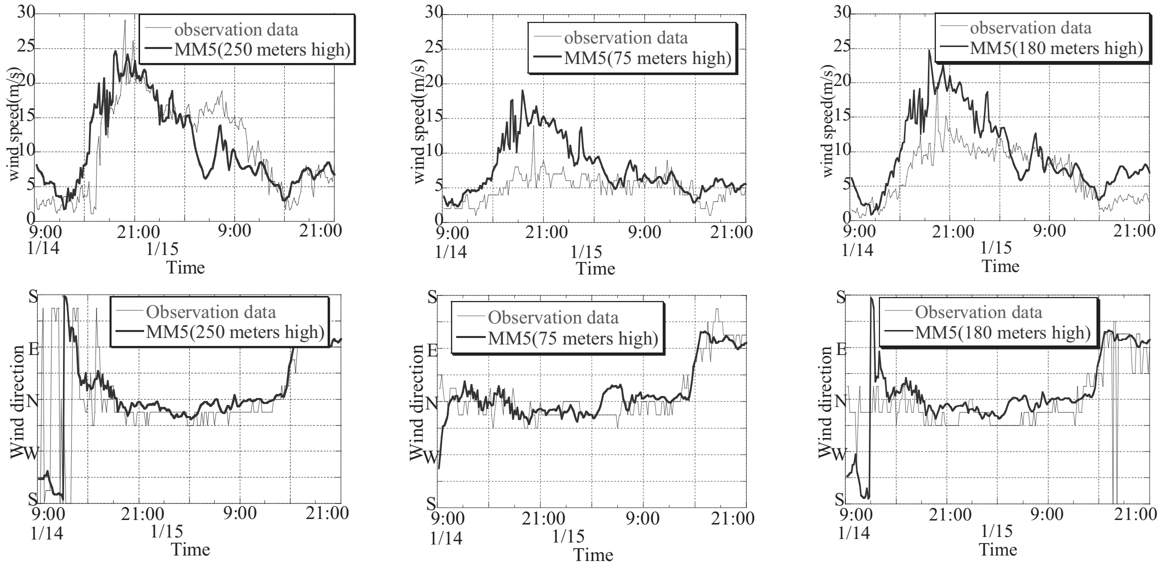
Figure 5 illustrates the instantaneous wind speed vectors and contours in the near wake of the high-rise building. It can be seen that the wind speed at point 4 was high because the flows converged inside the street at the side of the high-rise building. The position of the point 6 is behind the high-rise building. The reverse flow with fine structures can be recognized, fluctuation of wind direction is presumed to be very large in this region.

Figure 6 displays the relations between the LES results and observational data for 10-minute statistics near the ground surface ((a) mean wind speed, (b) maximum instantaneous wind speed and (c) turbulence intensity). LES data of mean wind speed with lower values are in good agreement with the full-scale measurement data. However, LES data of mean wind speed with higher values tend to be larger than the observational results. The maximum instantaneous wind speeds show the same tendency as the mean wind speed. The turbulence intensities estimated by LES are larger than the observational data.

WIND FLOWS IN URBAN CANOPY

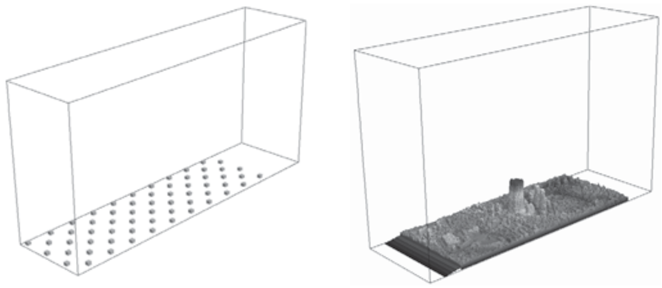
Figure 7 illustrates a numerical model for LES at the Marunouchi area in Tokyo. We can recognize several tall buildings at computational main regions and imagine the urban canopy layer is formed at this area. Table 2 shows the size and the grid numbers of the computational domains for urban canopy.

Figure 8 illustrates the instantaneous wind flow patterns within an urban canopy at Marunouchi area of Tokyo. We can recognize the turbulent flow structures with various



(a) Roppongi (b) Ootemachi (Meteorological observatory) (c) Marunouchi

Fig. 1. Comparison between MM5 results and the observational data on the rooftop of high-rise building at the center of Tokyo

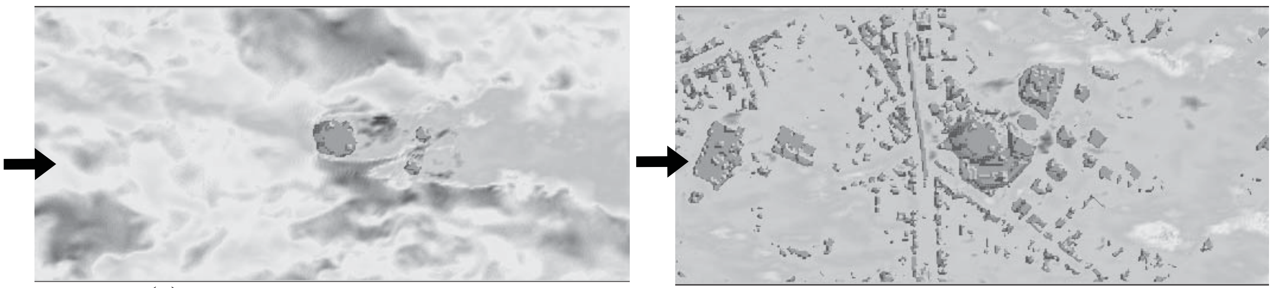


(a) Driver region (b)Main region

Fig. 2 Numerical model for an isolated tall building

Table.1 Computational region for an isolated tall building

	Driver region			Main region		
	X	Y	Z	X	Y	Z
Domain(km)	2.5	0.625	1.25	2	0.625	1.25
Grid points	500	125	97	400	125	97
Grid size(m)	5	5	5 ~ 37	5	5	5 ~ 37



(a) Upper wind (about 100m) (b)Near the ground surface

Fig. 3 Instantaneous wind speed around a high-rise building

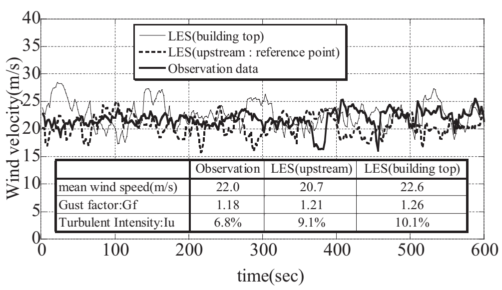


Fig. 4 Comparison of LES and observation; time-series of wind speed at higher position

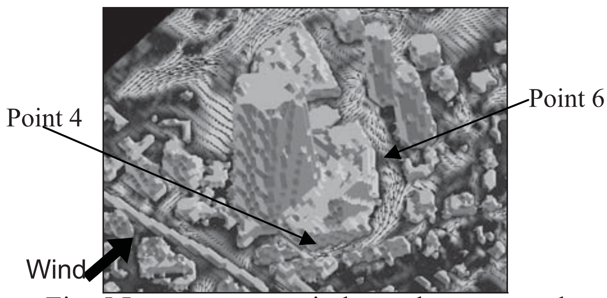
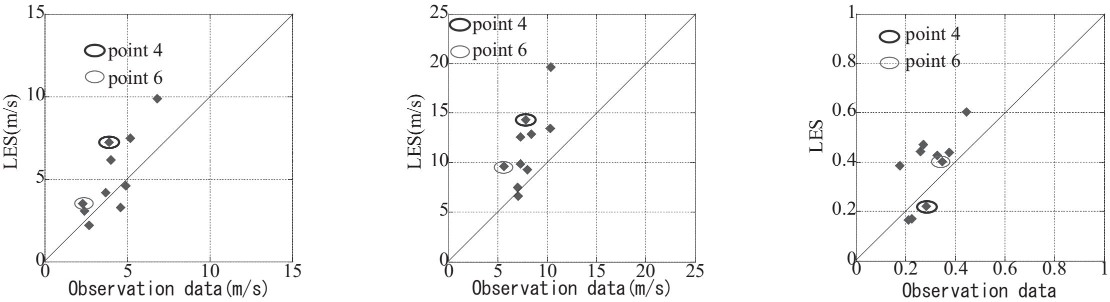
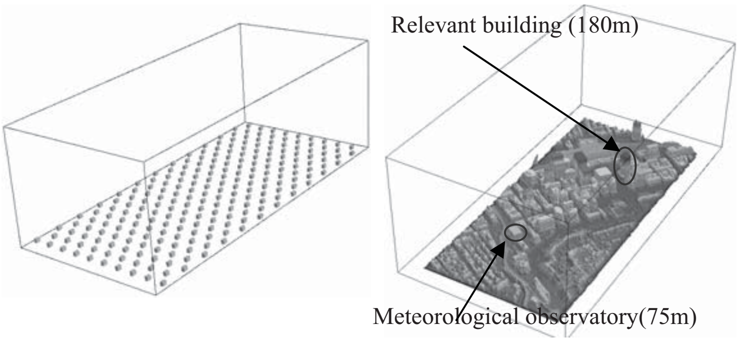


Fig. 5 Instantaneous wind speed vectors and contours



(a)mean wind velocity (b)maximum wind speed (c)turbulent intensity

Fig. 6 The comparison of LES results and observational data for the 10-minute statistics near the ground surface



(a) Driver region (b)Main region

Fig. 7 Numerical model for urban canopy

Table.2 Computational region for urban canopy

	Driver region			Main region		
	X	Y	Z	X	Y	Z
Domain(km)	2.4	1.08	0.8	2.16	1.08	0.8
Grid points	600	270	100	540	270	100
Grid size(m)	4	4	3 ~	4	4	3 ~

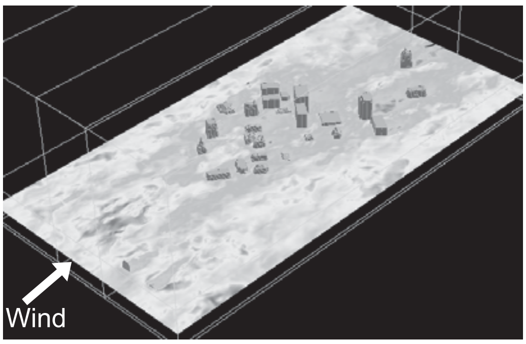


Fig. 8 Instantaneous wind speed in urban canopy

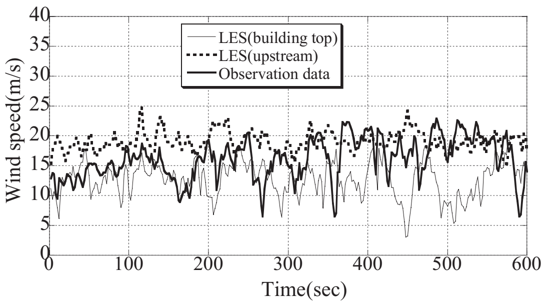


Fig. 9 Comparison of LES and observation; time-series of wind speed at higher position

Table.3 Comparison among observational data, MM5 results and LES+MM5

	Relevant building	Meteorological observatory
Observational data	10.0(m/s)	5.0(m/s)
MM5 results	16.6(m/s)	10.4(m/s)
LES+MM5(combination height:125m)	14.1(m/s)	8.6(m/s)
LES+MM5(combination height:250m)	11.9(m/s)	7.3(m/s)

Table.4 The comparison of LES results and observational data at a higher position

	Gust factor	Turbulent Intensity
Observational data	1.48	22.0(%)
LES(building top)	1.52	23.0(%)
LES(upstream)	1.30	8.7(%)

scaled vortices among complex buildings, because turbulent boundary layer is largely deformed by very rough condition at the ground surface. At a height of 100m, we can find a separated shear layer and vortex-shedding around the high-rise building. Near the ground, dominant flows can be seen along the main street.

The LES wind velocity at the reference point can be given as a dimensional value by using the absolute value predicted by MM5 at the same location. In this study, we consider two cases of height positions as a reference point and examine applicability of a reference velocity at the reference point to transform the LES results to be dimensinalized. One case is set to the height of 125m(about five times of averaged building height) and the other is 250m (about ten times of averaged building height).

Table 3 compares the wind velocity data at the rooftop among observational data, MM5 results and LES results based on MM5. The LES+MM5 results are closer to the observational data than the only MM5 data. According to Figure 8, the height of 125m is within the urban canopy but the height of 250m is above the canopy. So the case predicted by the reference height of 250m show the better results for the wind velocity at the rooftop.

Figure 9 compares the LES results with the observational data for the time series of wind speed at the rooftop over Marunouchi area for ten minutes. We can see that the time history at the rooftop is much affected by the surrounding tall building and shows a much larger fluctuation. We can also see a shift to high-frequency region at rooftop data by the surrounding circumstances. Gust factor and turbulence intensity in Table 4 estimated by LES are in satisfactorily good agreement with the observational results.

CONCLUSIONS

This study has aimed at estimating high wind in an actual urban area during during cyclogenesis by the combination of LES and MM5 computational techniques. A sophisticated numerical model in an actual urban area has been constructed using GIS data with high resolution, and the inflow boundary condition has been given by numerically simulating the turbulence characteristics of natural wind flow over rough ground surface. The absolute wind speeds at specific location inside the city were calculated by LES results combined with the MM5 results. The obtained results are summarized as follows.

Upper wind at a position sufficiently higher (about 250 meters) than an urban canopy layer is appropriate to give a velocity at the reference point.

With regard to the upper wind at the rooftop of the tall building, LES results combined with the meso-scale meteorological model can show reasonably good agreement with the observational data of mean velocity, velocity fluctuation and peak values even for the case of tall building within the urban canopy.

For wind flows near the ground surface, the present sophisticated model has the advantage that the absolute values of maximum instantaneous wind speed as well as mean wind can be evaluated. Also, local increase and decrease in surface winds can be understood by analyzing the flow structures based on the computed LES results.

With regard to the unstable meteorological condition, such as the typhoon attack or the explosive cyclogenesis, it is not clear whether the present numerical model can necessarily generate the predicted results sufficiently consistent with the observational data, because of vague reliability to robustness of the solutions obtained by the meso-scale meteorological model. We need some ideas for establishing the sophisticated model.

REFERENCES

Goldstein D., Handler R. and Sirovich L., 1993, "Modeling a No-Slip Flow Boundary with an External Force Field", *J. Comput. Phys.,* Vol.105, pp.354-366.

Kishida, T., Takei, Y., Tamura, T., Okuda, Y. and Nakamura, O., 2009, "Numerical Simulation of Strong Wind around Super High-Rise Building ", *Theoretical and Applied Mechanics Japan.,* Vol.57, pp.469-479.

Lund, T. S., Wu, X., and Squires, K. D., 1998, "Generation of Inflow Data for Spatially-Developing Boundary Layer Simulations", *Journal of Computational Physics*, Vol.140, pp.233-258.

Nozawa, K., and Tamura, T., 2002, "Large Eddy Simulation of the Flow around a Low-Rise Building in a Rough-Wall Turbulent Boundary Layer", *J.Wind Eng. Ind. Aerodyn*., Vol.90, pp.1151-1162.

Schlichting, H., 1979, "Boundary Layer Theory", *McGraw -Hill*.

Tamura, T., 2008a, "Towards Practical Use of LES in Wind Engineering", *J.Wind Eng.Ind.Aerodyn.*, Vol.96, pp.1451-1471.

Tamura, T., Takei, Y., Kishida, T., Okuda, Y., and Tamari, M., 2008b, "Hybrid Analysis of Meteorological Model and LES for Strong Wind in Urban Area", *Proceedings of the 20th national symposium on wind engineering*, pp.49-54. (in Japanese)

Tamura, T., Kishida, T., Okuda, Y., Nakamura, O., and Miyashita, K., 2009, "LES Estimation of Strong Wind in Actual Urban Area", *J.Struct. Constr. Eng., AIJ*. No.636, pp.215-223. (in Japanese)