Spatial Distribution of the Gust Index over an Urban Area in Tokyo

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1. Introduction

Tokyo is an example of an enormous urban area where the inhabitant reaches almost 40 million in the year 2015 as reported by the United Nations. The wind flow over an urban area induced the gusty condition due to its heterogeneous landscape. It might lead to the unpleasant events either towards the pedestrian or any structure within this area. It motivates a study to understand and represent the situation by an indicator called gust index. Therefore, a feasible and realistic large eddy simulation (LES) paired with the lattice Boltzmann method (LBM) over a 2 m resolution of a huge urban domain of Tokyo was conducted. This paper also proposed an appropriate definition of the gust index that characterized the level of gustiness of the urban area. The gust index was calculated by normalizing the maximum wind speed, u_{max} in 10 minutes time duration to the free stream velocity, U_∞. An understandable gust index map was prepared for an urban area in Tokyo. It can be referred to point out the area that creates the high gust occurrence. Several urban parameters that contribute to the high gust index also will be presented.

2. Numerical Model

A large eddy simulation (LES) that applied the lattice Boltzmann method (LBM) was executed over a huge computational domain. The same method over a square plane section of 10 km × 10 km urban area of Tokyo with 1 m resolution was conducted by Onodera et al. (2013). The domain contained a real building data and the particle motion was used to visualize the wind flow over this Tokyo urban area. This research encourages an urban meteorological analysis specifically for the wind flow characteristics within a huge and real urban area.

2.1 Lattice Boltzmann method (LBM)

As stated in Huda et al. (2015) the lattice Boltzmann method (LBM) doesn't need any further approximation as the formulation of its kinetic theory is in a discrete form. The LBM describes the evolution of the particles which are allowed to move only with a finite number of velocities. These particles act like the fluid flow by existing in a uniform lattice. At each time step, the particles move to neighboring lattice sites, where a system of hard spheres interacting only by elastic collisions locally in which their velocities change rapidly. The state of the system is specified at any time by giving the positions, $\boldsymbol{q}$ and velocities, $\boldsymbol{v}$ of n number of particles as $(\boldsymbol{q}_1, \boldsymbol{v}_1; \ldots; \boldsymbol{q}_n, \boldsymbol{v}_n)$. The state at any other time is determined by solving the equation of motion. The information on the microscopic behavior of the particles used in order to calculate its macroscopic properties such as the density. A millions number of particles are possible to be solved by approximating a discrete mass distribution with a continuous mass distribution function as $f(\boldsymbol{q}, \boldsymbol{v})d\boldsymbol{q}d\boldsymbol{v}$.

The simplicity and the locality of the LBM operations compensate the conventional continuity in Navier-Stokes equation. Its microscopic approach gave a clear physical depictions and easy in implementing the boundary condition. The absence of global numerical operation enables the high parallel algorithm efficiency of this method. A complex simulation which usually becoming problematic for a conventional numerical scheme is feasible by using this method. The LBM is applied to simulate the fluid flows at high Reynolds numbers with large eddy dynamics.

2.2 Large eddy simulation (LES)

The turbulence model in the large eddy simulation (LES) separated the resolved and unresolved fluid phenomena. The LBM resolved the flow dynamics of large-scale structures on a grid scale (GS) which recovered the macroscopic properties. The coherent-structure Smagorinsky model (CSM) is used to deal with a large scale simulation domain which enclosed a real and complex urban area. Details can be referred to Kobayashi et al. (2008) and Kobayashi (2005). The eddy-viscosity subgrid-scale (SGS) will modeled the turbulent structures smaller than grid scale based on the assumption of local equilibrium between production and dissipation of turbulent kinetic energy. Onodera et al. (2013) describes the list of equations used in this simulation.

3. Gust Index

Wind gustiness exhibits an abrupt disturbance in the calm wind flow for a short period of time. It might cause by many sources such as the change in the synoptic scale or meso-scale wind phenomena, the micro-scale surface friction and temperature, the building scale where the wind deflects due to the obstacle and etc. It is also a great challenge to define a standard gustiness level. A common term of this gustiness level called as gust factor. This term itself needs an intensive understanding of its definition, method and scale of the measurement, its application, and many more. However, in general, those gust factors were defined as Eq. (1):

$$G = \frac{u_{max}}{\bar{U}} \quad (1)$$

where G is the gust factor, u_{max} is the maximum wind speed in a period of time and $\bar{U}$ is the mean wind speed of a certain averaging time.

By considering the purpose of this research and the simulation conditions, a new definition of the gustiness level is introduced. This paper will use the gust index instead of the established gust factor terms in order to avoid the misperception with the previous study. The gust index, which is u_{max} divided by the free stream velocity, U_{∞} chosen to map the gust index distribution. Eq. (1) was redefined as Eq. (2) as below.

$$GI = \frac{u_{max}}{U_{\infty}} \quad (2)$$

The free stream velocity, U_{∞}, considered as a feasible denominator as this velocity is independent with the urban parameter such as roughness length and displacement height. This velocity can be considered as homogeneous in space for a certain time step. In addition, the reference level of this velocity is higher than the developed boundary layer height and will not be influenced by this factor.

4. Simulation Condition

The wind flow simulation over the Tokyo urban area consists of a computational domain which is longer in the stream wise and narrow in the span wise. The domain size is 19.2 km in stream wise $(\boldsymbol{x})$, 4.8 km in span wise $(\boldsymbol{y})$ and 1 km in vertical direction $(\boldsymbol{z})$. This reproduced 2 m grid resolution domain contained a realistic building height data. A neutral atmospheric condition (i.e. shear driven turbulence) applied in this simulation. The inlet boundary was a continuous bulk uniform inflow of 10 m s^{-1}, blown towards inland from a coastal area that includes the Tokyo Bay. The radiation boundary applied at the outlet. The periodic boundary condition used in the span wise. The bottom and the top boundary was non slip and slip condition respectively. The simulation time was up to 6960 seconds and the calculation done by 900 GPU cores of TSUBAME 2.5.

5. Spatial distribution of the gust index

Figure 1 shows the spatial distribution of the gust index on the first horizontal grid, which is at 2 m height. Referring to Eq. (2), this gust index map was plotted by normalizing the maximum wind speed in 10 minutes interval, u_{max}, to the free stream velocity, U_{∞}, at 600 m which is above the boundary layer height.

Apparently, the high gust index distribution can be seen near the domain inlet where there is just a flat coastal surface compared to the highly dense and rough area towards the domain down stream. However, there are also high gust indexes spotted in several locations within the built-up area. The dominant component to these high gust indexes will be differed locally as u_{max} in Eq. (2) can be either greatly contributed by the mean wind speed, $\bar{U}$, or the turbulent part, u'. Stull (1988) separated these wind components as in Eq. (3). The detailed analysis of this matter will be considered in the future works.

$$u_{max} = (\bar{U} + u')_{max} \quad (3)$$

Figure 2 (a) – (d) illustrate the selected locations of high gust index occurrence. The corresponding builds morphology overlay this gust index map to show the relation between these two features. In general, these four chosen areas show that the urban parameters such as the plan area index, building geometry and street angle can be the factors that induce the high gust index.

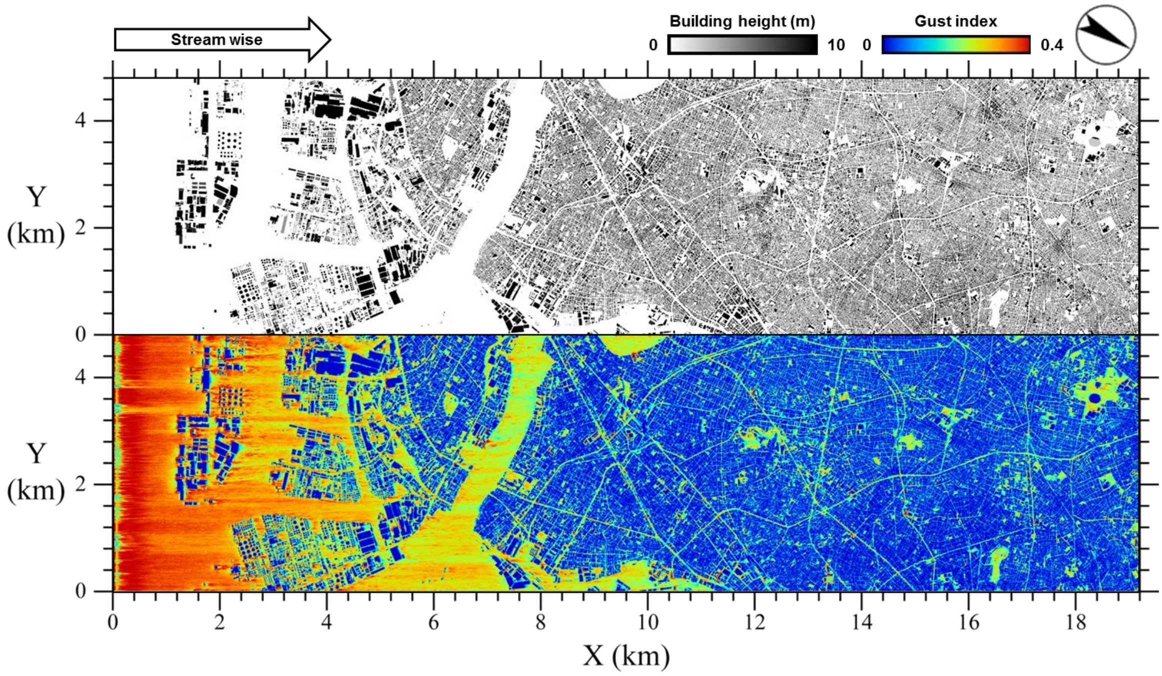

Fig. 1 A realistic building height data includes in the simulation domain (top) and the gust index map at 2 m height (bottom).

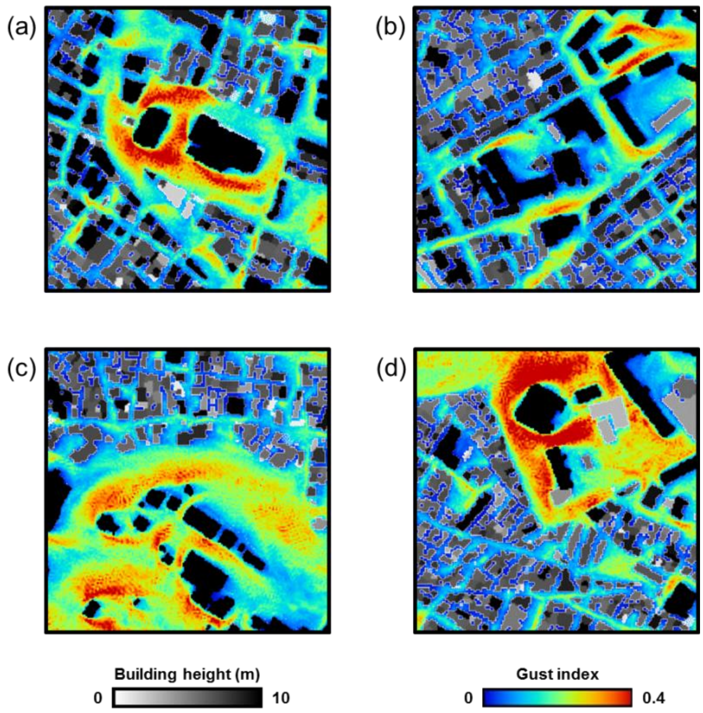

Fig. 2 Selected 320 × 320 m^2 areas of high gust index with the correspond building morphology.

6. Concluding Remarks

There are several points that have been highlighted throughout this paper. The large eddy simulation was executed by pairing it with the lattice Boltzmann method to study the wind flow over an urban area of Tokyo. The simplicity and locality of this method make the simulation over a huge, high resolution and complex geometry of an urban area was feasible and successfully conducted. A gust index definition which considered the ratio of the maximum wind speed, u_{max}, to the free stream velocity, U_∞, proposed. This normalized value used to illustrate the gust index distribution for the whole simulation domain. The urban parameters such as the plan area index, building geometry and street angle might contribute to the high gust index in a certain location.

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