NUMERICAL ANALYSIS OF THE MOMENTUM TRANSPORT AND TEMPORAL AND SPATIAL SCALES OF TURBULENT COHERENT STRUCTURES IN THE URBAN BOUNDARY LAYER USING LARGE EDDY SIMULATION

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ABSTRACT

Numerical analysis is performed on an urban model to investigate turbulent coherent structures in urban boundary layer (UBL) using large-eddy simulation (LES). To confirm the accuracy of LES, its results are compared with those of a wind tunnel experiment. Streamwise mean wind velocity and streamwise turbulent intensity calculated using LES are generally identical to results of a wind tunnel experiment. Four-quadrant and correlation coefficient analysis are performed to investigate momentum transport and temporal and spatial scales of turbulent coherent structures in UBL. Four-quadrant analysis results show that strong ejections and sweeps are generated at the top of urban canopy because of inflection point instability of streamwise mean wind velocity. They correspond to drag force above and below the top of urban canopy respectively. Streamwise integral scales are calculated from correlation coefficients. As height increases, streamwise integral time scales decrease, however, streamwise integral length scales remained almost constant.

Keywords: Large-eddy simulation, Turbulent coherent structure, Four quadrant analysis, Integral scale

1. Introduction

Urban heat island phenomena and air pollution have become serious issues in urban spaces. To arrive at solutions to these problems using design concepts for buildings and urban spaces, it is necessary to predict the urban climate accurately. However, conventional numerical models for predicting the urban climate are not sufficiently accurate at micro-scale and meso-scale. At micro-scale, Reynolds Averaged Navier-Stokes Simulation (RANS), which facilitates the analysis of average flow fields, is widely used to predict the flow fields for buildings and city blocks in urban spaces. However, RANS is not sufficiently accurate for simulating urban canyon and urban boundary layer (UBL) [Yoshie et al. (2012)]. At the meso-scale, a regional climate model is widely used to predict local climate. However, the regional climate model is not adequately accurate for urban spaces because prediction accuracy of momentum, heat, and mass fluxes at UBL which yield boundary conditions of urban space in the regional climate model, is not sufficiently accurate [Roth et al. (1993a); Roth et al. (1993b); Roth et al. (1995); Kanda et al. (2000)]. To improve the prediction accuracy of these models, it is necessary to investigate the contribution of turbulent coherent structures to momentum, heat, and mass transport and the mechanism of transport of turbulent coherent structures on flow fields of urban spaces to include the influence of turbulent coherent structures into turbulence modeling.

Turbulent coherent structures generated in UBL significantly influence momentum, heat, and mass transport in urban spaces [Michioka et al. (2011)]. It is important to clarify the mechanism of generation, its contribution to transport, temporal and spatial distributions and the scale of turbulent coherent structures to improve prediction accuracy of numerical models.
Raupach et al. (1996) lists some methods such as variable interval time averaging (VITA), window averaged gradient (WAG), four-quadrant analysis, correlation coefficient, integral scale, wavelet analysis, and visualization used to investigate turbulent coherent structures. In this study, four-quadrant analysis, correlation coefficient, and integral scale are used to investigate turbulent coherent structures. Four-quadrant analysis is a method used to investigate the contribution of turbulent coherent structures to momentum transport. Correlation coefficient and integral scale are methods used to investigate temporal and spatial scale of turbulent coherent structures. Inagaki et al. (2006) and Maruyama et al. (2009) investigated momentum transport and temporal and spatial scales of turbulent coherent structures in UBL by adopting an observational survey of outdoor urban scale model and using four-quadrant analysis, correlation coefficients, and integral scale. In order to investigate turbulent coherent structures in the UBL in more detail, we subjected an urban model to numerical analysis by applying large-eddy simulation (LES). From the results of LES, momentum transport and temporal and spatial scales of turbulent coherent structures in UBL are investigated using four-quadrant analysis, correlation coefficients, and integral scale.

2. Physical Model and Numerical Method

Fig. 1 illustrates the urban model. The model is set up with reference to the wind tunnel experiment conducted by Uehara et al. (2000). Cubic urban model blocks with dimensions of H×H×H (H=100 mm) and a scale of 1 to 300 are arranged at H intervals in the direction of the x-axis and at 0.5H intervals in the direction of the y-axis. On the upwind side of the urban model blocks, roughness blocks with dimensions of H×H×0.5H are arranged in a staggered configuration at H intervals in the direction of the x-axis and H intervals in the direction of the y-axis.

Numerical analysis is performed with OpenFOAM, an open source computational fluid dynamics (CFD) analysis software. Subgrid scale (SGS) model of LES is a standard Smagorinsky model. The Smagorinsky constant (C_s) is 0.18. Table 1 lists the conditions of the numerical analysis and the boundary conditions in detail. For inlet boundary condition, the turbulent intensity $\tilde{u}=0.015$ m/s is added to the uniform flow U=1.5 m/s. For ground boundary condition and building boundary condition, wall function, Spalding’s law, is used in order to reduce the number of grid near wall. Fig. 2 shows the domain of the numerical analysis in which uniform interval analytical grid is used.
3. Results and Discussions

3.1. Comparison of numerical analysis and wind tunnel experiment

Fig. 3 shows the results of LES and wind tunnel experiment at the center of the urban canyon in the fifth row (x/H = 38.5, y/H = 3.75). Streamwise turbulent intensity, turbulent kinetic energy, and Reynolds stress are the largest at the top of the urban canopy (z/H = 1.0) since the gradient of streamwise mean wind velocity is the largest at that height. The turbulent kinetic energy and Reynolds stress calculated using LES are smaller than those obtained in the wind tunnel experiment at some heights. The reason of this may be thought that the results in LES do not include SGS components. It is necessary to use an analytical grid with high resolution to decrease the influence of SGS components and reproduce the results of the wind tunnel experiment in the LES. However, in this study, the resolution of the analytical grid is not sufficient. The streamwise mean wind velocity and the streamwise turbulent intensity calculated using LES is generally identical to those obtained in wind tunnel experiment. The accuracy of the LES is sufficient for the objectives of our study.

3.2. Four-quadrant analysis

Four-quadrant analysis is a method used to investigate the contribution to the momentum transport of turbulent coherent structures. Horizontal wind velocity and vertical wind velocity are decomposed into ensemble average components, <u> and <w>, and variation components, u' and w', that is u = <u> + u' and w = <w> + w'. Fig. 8 shows the diagram of four-quadrant analysis. In this analysis, variation components of horizontal wind velocity, u', and vertical wind velocity, w', are classified as one of four kinds of events according to their quadrant in the u'-w' plane. The events classified as the first quadrant (u' > 0, w' > 0) are called outward interactions, those classified as the second quadrant (u' < 0, w' > 0) are called ejections, those classified as the third quadrant (u' < 0, w' < 0) are called inward interactions, and those classified as the fourth quadrant (u' > 0, w' < 0) are called sweeps. Ejections are events in which low-speed fluid bodies flow upward, whereas sweeps are those in which high-speed fluid bodies flow downward. These contribute to the momentum transport from upper side to lower side. Momentum transport of turbulent coherent structures from upper side to lower side corresponds to drag forces in UBL. Outward interactions are events in which high-speed fluid bodies flow upward while inward interactions are those in which low-speed fluid bodies flow downward. They contribute to the momentum transport from the lower side to the upper side.
Fig. 4, Fig. 5, and Fig. 6 show results of four-quadrant analysis at the centers of urban canyon \((x/H = 38.5, \ y/H = 3.75)\) and urban street \((x/H = 38.5, \ y/H = 3.00)\) in fifth row. Sweeps occur more frequently than ejections as height increases. However, the momentum transport of ejections becomes larger than that of sweeps. At the top of the urban canopy \((z/H = 1.0)\), frequency of occurrence and momentum transports of both ejections and sweeps are the largest and almost identical. According to Raupach et al. (1996), the inflection point instability of the streamwise mean wind velocity generates strong sweeps. The inflection point of the streamwise mean wind velocity is the point at which its gradient becomes the largest, and the shear stress by the streamwise mean wind velocity also becomes the largest. This explains the increase in momentum transport of sweeps at the top of urban canopy. The results of four-quadrant analysis show that momentum transport of ejections also increases at the top of urban canopy. This indicates that inflection point instability of streamwise mean wind velocity generates both strong sweeps as well as strong ejections. Because strong ejections and sweeps generated at the top of urban canopy are transferred upwards and downwards respectively, momentum transport of ejections at greater heights, and momentum transport of sweeps at lesser heights also large. The strong ejections and strong sweeps generated at the top of urban canopy correspond to the drag force above and below the top of urban canopy respectively.

Fig. 7 shows skewness of horizontal and vertical wind velocity at the center of urban canyon \((x/H = 38.5, \ y/H = 3.75)\) and urban street \((x/H = 38.5, \ y/H = 3.00)\) in fifth row. As the height increases, skewness of the horizontal wind velocity decreases and become negative, however that of the vertical wind velocity increases and become positive. This indicates that as height increases, sweeps occur more frequently than ejections, however, momentum transport of ejections become larger than that of sweeps. This result is consistent with the results of four-quadrant analysis.

3.3. Correlation coefficient and integral scale

Correlation coefficient and integral scale are methods used to investigate the temporal and spatial scale of turbulent coherent structures. Autocorrelation coefficient and space correlation coefficient are expressed by equation (1) and equation (2) respectively. Autocorrelation coefficient signifies the relation between two values taken at different time points, whereas spatial coefficient signifies the relation between two values at different location. Integral time scale and integral length scales are expressed by equation (3) and equation (4). Integral time scale and integral length scale are calculated from autocorrelation coefficient and space correlation coefficient. Integral time scale shows the average of time scales, integral length scale shows the average of length scales for turbulent coherent structures.

Fig. 9 and Fig. 10 show the autocorrelation coefficients and the space correlation coefficients at the center of urban canyon \((x/H = 38.5, \ y/H = 3.75)\) in fifth row. Table 2 lists streamwise integral time scales and integral length scales calculated from autocorrelation coefficients and space correlation coefficients with equation (3) and equation (4) at the center of urban canyon \((x/H = 38.5, \ y/H =3.75)\) in fifth row. As height increases, streamwise integral time scales decrease, however, streamwise integral length scales remain almost constant. The results of four-quadrant analysis indicate that frequency of occurrence of each event, shown in Fig. 4, is distributed in UBL according to height. However, Table 2 shows that the average of streamwise length scales of coherent structures remains almost constant. Therefore, there is a possibility of each turbulent coherent structure having its unique length scales according to height.
\begin{align}
RT_{u} &= \frac{\langle u'(x,t)u'(x,t+dt) \rangle}{\sqrt{\langle u'^2(x,t) \rangle} \sqrt{\langle u'^2(x,t+dt) \rangle}} \quad (1) \\
RS_{u} &= \frac{\langle u'(x,t)u'(x+dx,t) \rangle}{\sqrt{\langle u'^2(x,t) \rangle} \sqrt{\langle u'^2(x+dx,t) \rangle}} \\
IT_{u} &= \int_{-\infty}^{+\infty} \frac{\langle u'(x,t)u'(x+dt,t) \rangle}{\sqrt{\langle u'^2(x,t) \rangle} \sqrt{\langle u'^2(x,t+dt) \rangle}} dt \quad (3) \\
IS_{u} &= \int_{-\infty}^{+\infty} \frac{\langle u'(x,t)u'(x+dx,t) \rangle}{\sqrt{\langle u'^2(x,t) \rangle} \sqrt{\langle u'^2(x+dx,t) \rangle}} dx \quad (4)
\end{align}

4. Conclusions

Numerical analysis is performed on the urban model using LES. From the results, momentum transport and temporal and spatial scales of turbulent coherent structures in UBL are investigated using four-quadrant analysis, correlation coefficient, and integral scale. As height increases, the frequency of occurrence of sweeps becomes larger than that of ejections. However, momentum transport of ejections becomes larger than that of sweeps. Ejections and sweeps are generated by inflection point instability of the streamwise mean wind velocity at the top of urban canopy \((z/H = 1.0)\). The strong ejections and sweeps generated at the top of urban canopy are transferred upwards and downwards respectively. They contribute significantly to momentum transport in UBL from upper side to lower side and correspond to drag force above and below the top of urban canopy respectively. As height increases, integral time scales become smaller, however, integral length scales remain almost constant. This result is consistent with the result that the streamwise mean wind velocity increases as the height become larger.
Fig. 3 Statistics of turbulence at the center of urban canyon (x/H = 38.5)
Fig. 4 Occurrence frequency of each quadrant's events

a) Center of urban canyon (y/H = 3.75)  b) Center of urban street (y/H = 3.00)

Fig. 5 Momentum transport of each quadrant's events

a) Center of urban canyon (y/H = 3.75)  b) Center of urban street (y/H = 3.00)

Fig. 6 Momentum transport of each quadrant's events per occurrence frequency
a) Center of urban canyon (y/H = 3.75)  
Fig. 7 Skewness of the horizontal and vertical wind velocity (x/H = 38.5)

b) Center of urban street (y/H = 3.00)

Table 2: Integral scale (z/H=1.5, 2.0, 2.5)

<table>
<thead>
<tr>
<th>z/H</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time scale</td>
<td>1.05</td>
<td>0.97</td>
<td>0.85</td>
</tr>
<tr>
<td>Length scale</td>
<td>2.1H</td>
<td>1.9H</td>
<td>2.2H</td>
</tr>
</tbody>
</table>

Fig. 8 Diagram of four-quadrant analysis

Fig. 9 Autocorrelation coefficient at the urban canyon center (x/H = 38.5)

Fig. 10 Space correlation coefficient at the urban canyon center (x/H = 38.5)
References


