Spatial and temporal scales of coherent turbulence over outdoor reduced urban scale model

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Abstract

This study investigated the spatial and temporal scales of the coherent turbulence based on the experiment in the outdoor reduced urban scale model. In the experimental site, we conducted a multi-points measurement of the turbulent fluctuations. Multiple numbers of sonic anemometers were aligned along streamwise and spanwise directions at the same height, and measured 3-dimensional velocities and temperatures in-sync. These datasets were analyzed using the two-point correlation to figure out the spatial and temporal scales of coherent turbulence developed over building-like roughness, and its convective velocity.

This analysis resulted in the convective velocity of the inactive motion, which is irrelevant to the vertical momentum transfer and attributed to the mixed layer convection, of about 1.6 time faster than the horizontal mean velocity at 2 times the building height. This relationship is for the magnitude of the horizontal mean velocity more than 1 m s^{-1}. On the other hand, the convective velocities of smaller eddies (e.g. active motion) are slower than inactive motion and faster than the local mean velocity.

The distribution of the two-point correlation of streamwise velocity for horizontal separation distances, normalized by individual roughness heights, was almost consistent between the building like roughness and the vegetation. The aspect ratio of their horizontal distribution was well preserved irrespective of the types of surface roughness.

Key words: two-point correlation, outdoor urban model experiment, coherent structure of turbulence

1. INTRODUCTION

Coherent motion of turbulence is considered to determine the turbulent transport process of momentum, heat and other scalars within a surface layer. However, its characteristics are seldom understood especially in urban boundary layer. Therefore, we experimentally evaluated its characteristics using a comprehensive outdoor scale model experiment for urban climate (COSMO). Specifically, we focused the investigation on the spatial and temporal scales of coherent turbulence.

As indicated in the previous report (Inagaki and Kanda 2009, "*Structure of active turbulence over outdoor reduced urban scale model*", *ICUC-7*), the atmospheric surface layer is composed of active and inactive motions. The former is directly responsible for the net turbulent transport process and can be scaled with inner-layer (surface-layer) variables (e.g. z'). The latter is not responsible for the turbulent transport process and scaled with outer-layer (mixed-layer) variables (e.g. z_i) since it usually originates from the mixed layer convection.

It is essential to investigate the active motion since it directly contributes to the turbulent transport processes within the atmospheric surface layer. However, it is difficult to do so because the active and inactive motions always coexist. Therefore, we applied a method to separate both modes, which is provided in the previous report (Inagaki and Kanda 2009).

For the analysis of turbulence developed over building-like roughness, the two-point correlation method was used to figure out convective velocity of the coherent turbulence, and the spatial and temporal scales of the active turbulence.

2. THEORETICAL BACKGROUND

2.1. Two-point correlation

Two-point correlation coefficient shows the degree of common relationships of the variables at two separate locations. In a quasi-steady flow, the correlation coefficient is defined as,

$$R_\phi(\vec{r},\Delta\vec{r},\Delta t) = \frac{\overline{\phi(\vec{r},t)\phi(\vec{r}+\Delta\vec{r},t+\Delta t)}}{\sqrt{\overline{\phi^2(\vec{r},t)}}\sqrt{\overline{\phi^2(\vec{r}+\Delta\vec{r},t+\Delta t)}}}\ , \tag{1}$$

where, ϕ is a physical variable as a function of location vector $\vec{r} = (x,y,z)$ (m) and time t (s), $\Delta\vec{r} = (\Delta x,\Delta y,\Delta z)$ and Δt are the separation vector for distance and time, respectively.

Now we consider the horizontally separated points in the same height. Then, if Taylor's frozen turbulence hypothesis is assumed, the correlation coefficient is expressed as a function of Δy and Δt as,

$$R_\phi(\Delta x, \Delta y) \sim R_\phi(U_c \Delta t, \Delta y) = \frac{\overline{\phi(y,t)\,\phi(y+\Delta y, t+\Delta t)}}{\sqrt{\overline{\phi^2(y,t)}}\sqrt{\overline{\phi^2(y+\Delta y, t+\Delta t)}}}. \quad (2)$$

where, U_c is a convective velocity of turbulent structure.

The convective velocity of turbulent motion could be estimated from the two-point correlation of separated measurement points along the streamwise direction. When a ‘frozen’ turbulence structure passes through the separated measurement points with a lag time τ_{peak}, the correlation coefficient becomes maxima at this lag time. Then, the convective velocity is estimated to be $U_c = \Delta x / \tau_{peak}$.

2.2. Method to separate the active and inactive modes

A method to separate the active and inactive motion was proposed in the previous report (Inagaki and Kanda 2009). The strategy of this method is that the inactive motion is estimated from the moving average in space along the spanwise direction (not in time nor space along streamwise direction). Then the velocity and temperature components are separated into moving averaged part and the residual part. This method is validated in the field experiment in COSMO. We could separate the residual component, which accounts for 92% of the total Reynolds stress, where most of the inactive components are filtered out if we could choose an appropriate size of the moving-average window. The detail description of this method is found in Inagaki and Kanda (2009).

3. EXPERIMENTAL SETUP

The COSMO experimental facility was constructed at the Nippon Institute of Technology in Saitama, Japan. There are 512 concrete cubes and 8-meter meteorological towers on a flat concrete plate (Figure 1). The cubes, which are 1.5 m (=H) on a side, are arranged regularly. Detailed descriptions of COSMO can be found in Inagaki & Kanda (2008).

To make two-point correlation analysis, the sonic anemometers were spatially distributed at a constant height of 2H from the ground. The horizontal location and the measurement period are shown in Figure 1 and Table 1. The locations CF and CB each include 15 sonic anemometers aligned along NE-SW axis. These experiments were conducted in 3 isolated periods.

Only the datasets that satisfy the following thresholds were analyzed; the deviation of the mean wind direction from the NW-SE axis is less than 5 degree, mean wind velocity is more than 1 m s^{-1}, and the magnitude of the atmospheric stability z'/L is less than 0.05 (neutral stratification).

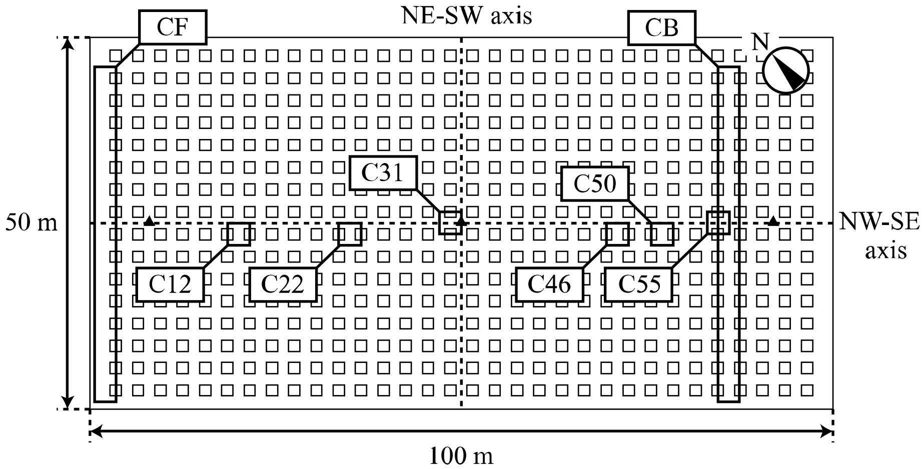

Figure 1 Schematic of COSMO experimental facility. C12, C22, C31, C46, C50, C55 include single anemometer. CF and CB include 15 sonic anemometers.

Table 1 Experimental period and the location of the measurement.

Name	CF	C12	C22	C31	C46	C50	C55	CB
Distance from CF (m)	0	16.65	32.15	46.5	68.05	73.65	82.5	84
Experimental term	T1	T3	T3	T2, T3	T2	T2	T2, T3	T1

Experimental periods are; T1: from November 9, 2006 to January 29, 2007, T2: from October 15, 2007 to December 3, 2007, T3: February 5, 2008 to February 10, 2008.

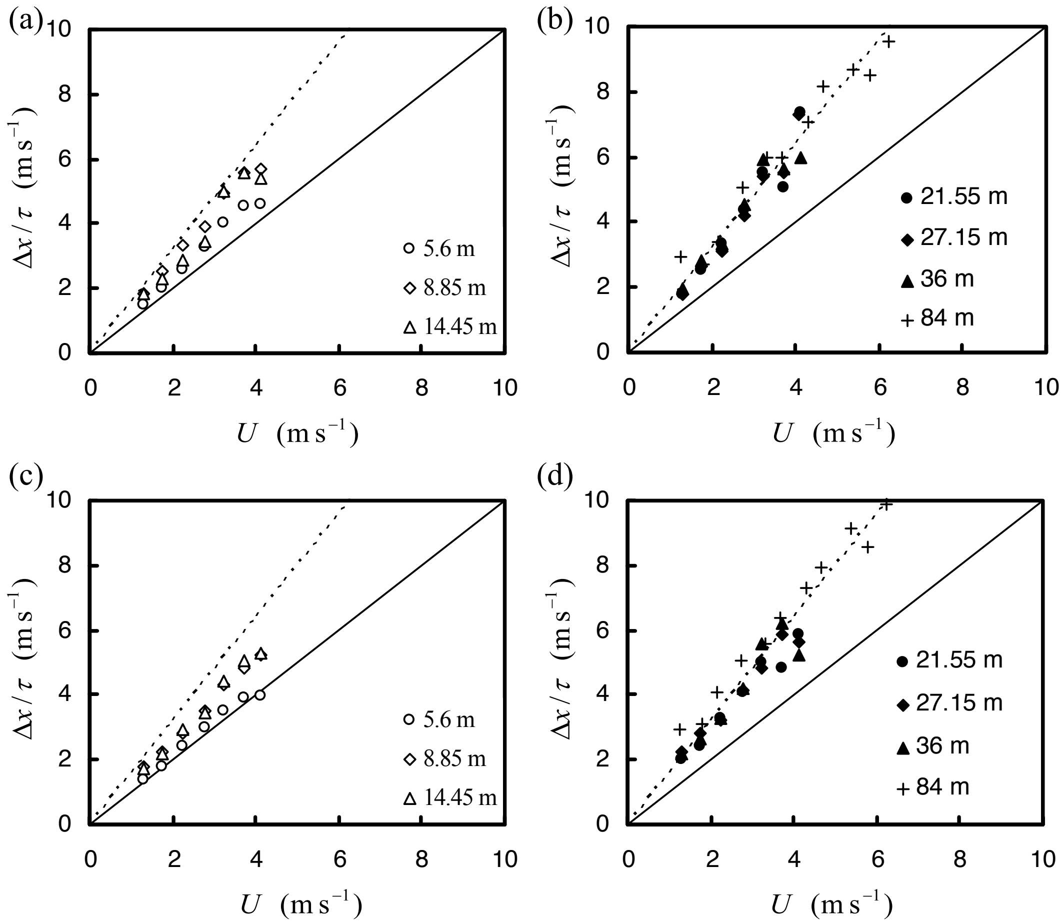

Figure 2 Convective velocities plotted on the horizontal mean velocity. The convective velocity is calculated from (a), (b) streamwise velocity and (c), (d) spanwise velocity fluctuations. The separation distances along streamwise direction are (a), (c) 5.6 ~ 14.45 m and (b), (d) 21.55 m ~ 36 m, and 84 m (for inactive motion only).

4. RESULTS

4.1. Convective velocity

Figure 2 shows the convective velocities plotted against U at 2H, estimated from the two-point correlation of u and v fluctuations. The averaging time was 3 minutes. When the separation distance is long enough, the convective velocities become almost consistent to $1.6U$. When the separation is small, the calculated convective velocities become smaller than $1.6U$ and larger than U.

We applied the decomposition of active and inactive motions to see their convective velocities. These two kinds of motions are expected to have different convective velocities, since their vertical extents are different, while the local mean velocity changes vertically. The datasets obtained at CF and CB in Figure 1 were used. The resulting convective velocity of the inactive motion was plotted on Figure 2(b) and (d). The convective velocity of inactive motion was also $1.6U$, which is consistent with the values observed at the large separation distance.

When the separation distance is long, small eddies that passed through the upwind probe rapidly dissipated or deformed until they arrive at the downwind probe. Therefore, such eddies do not contribute to the correlation coefficient. In contrast, the large scale motions, which are likely inactive motions, still preserve their shapes when they pass through the whole separation interval since their time scale is also large. As a result, the correlation peak tends to appear at the lag time of the large scale motion rather than that for small scale motion if the convective velocities of small and large scale motions are different. On the other hand, the smaller eddies could predominantly determine the correlation peaks when the separation distance is small enough to preserve the shape of small eddies during the lag time. Therefore, the convective velocity observed in the smaller separation distance would be attributed to that of smaller motions, although it is still not clear that this represents the convective velocity of active motion.

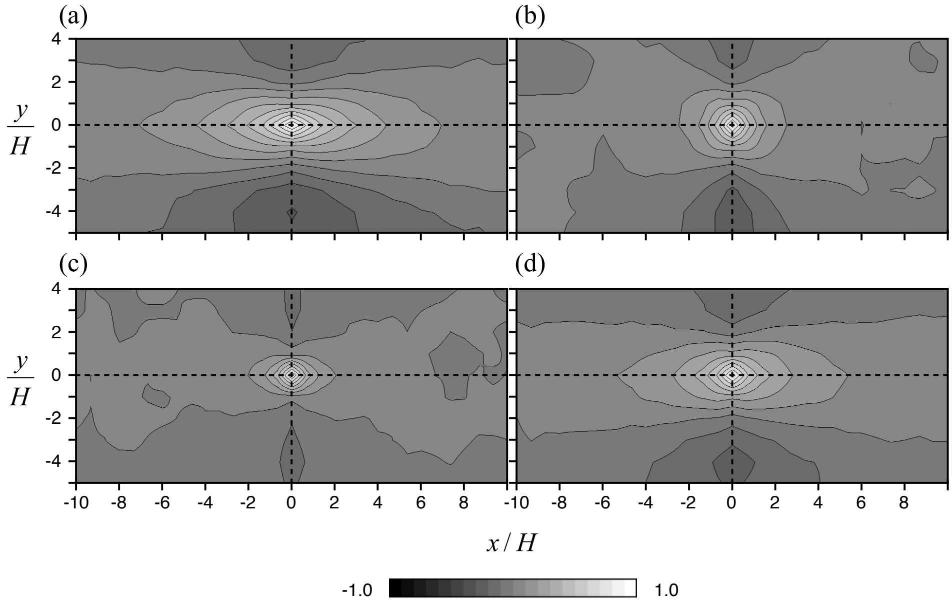

Figure 3 Two-point correlation coefficients of (a) streamwise velocity, (b) spanwise velocity, (c) vertical velocity, and (d) temperature fluctuations, plotted on the separation distance along streamwise and spanwise directions.

4.2. Spatial distribution of two-point correlation coefficient

We investigated the horizontal scale of the coherent turbulence using two-point correlation. The Taylor's frozen turbulence hypothesis is used to convert the lag time into the streamwise separation distance by multiplying the local mean velocity. The separation distances are normalized by H. To focus on the characteristics of active motion, the active components were extracted and used to calculate the two-point correlation.

Figure 3 shows the correlation coefficients for u, v, w, and temperature θ plotted on the separation distances along streamwise and spanwise directions. The distributions of u and θ are elongated along the streamwise direction, while those for v and w are more rounded in the horizontal field. These characteristics are consistent with those found in the vegetation canopy (Shaw et al. 1995), and in flat walls (Volino et al. 2007). Furthermore, the aspect ratio (i.e. spanwise versus streamwise directions) of the distribution of u is also consistent with the distribution observed by Shaw et al. (1995), which is about 5:1 (streamwise vs. spanwise). This means that this kind of distribution is geometrically similar irrespective of the types of roughness.

5. CONCLUSIONS

We demonstrated the correlation analysis using the datasets obtained in the outdoor reduced urban scale model to investigate the spatial and temporal scale of coherent turbulence. Concluding remarks are as follows;

1. The convective velocity of the inactive motion was about 1.6 times of U at 2H, when the magnitude of U is more than 1 m s^{-1}.
2. The convective velocity of active motion is lower than that for inactive motion within the atmospheric surface layer. Its magnitude is nearly comparable to U.
3. Analysis using two-point correlation resulted in a correlation of u that is higher along the streamwise direction compared to an equal magnitude of spanwise separation. This result is attributed to the existence of the coherent turbulence elongated along the streamwise direction.
4. The aspect ratio of this horizontal distribution of correlation coefficient of u is almost consistent to that observed in the vegetation canopy (Shaw et al. 1995), which is about 5:1 (streamwise vs. spanwise). This means that the coherent structure of u is geometrically similar irrespective of the types of roughness.

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