Structure of active turbulence over outdoor reduced urban scale model
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Abstract

This study investigated the coherent structure of turbulence within the atmospheric surface layer over building-like roughness. The horizontal distributions of coherent turbulence were determined by multipoint measurements of velocity fluctuations using sonic anemometers in a comprehensive outdoor scale model experiment for urban climate (COSMO). The velocity fluctuations observed in COSMO were decomposed into active and inactive contributions by applying an instantaneous spatial average in a small horizontal section. This method is validated on site and could separate the smaller scale motion, which accounts 92% of Reynolds stress, and the larger scale motion, which is almost inactive to the local Reynolds stress. The horizontal distribution of the active motion was represented by very large streaks of low momentum fluid elongated in the streamwise direction, similar to those found in several wind tunnel experiments and numerical simulations over various kinds of surface geometries.

Key words: active eddy, outdoor urban model experiment, coherent structure of turbulence

1. INTRODUCTION

The turbulent boundary layer is composed of active and inactive motions (Townsend 1976). The active motion directly contributes to the Reynolds stress and inactive motion does not contribute to it. Inagaki and Kanda (2009) also suggested that both kinds of mode exist within the atmospheric surface layer over building-like roughness. Therefore, turbulent transport process of momentum, heat and scalars, which is a major concern of this study, is expected to relate to the active motion. However, it is difficult to investigate this because the active and inactive motions always coexist.

We propose a method to separate both kinds of motions and validate the method using the datasets obtained in the comprehensive outdoor scale model experiment for urban climate (COSMO). The separation method is applied to figure out the horizontal distribution of the active motion that is also observed in COSMO.

2. Method to separate the active and inactive motions

We propose a method to separate the active and inactive turbulence to investigate coherent structures attributed to active motion. The method is based on the assumption that the active and inactive turbulence do not directly interact with each other because the size of the inactive motion is much larger than that of the active motion (Townsend, 1976). Then, the active and inactive turbulence can be linearly separated. The validity of this separation has been discussed by McNaughton & Laubach (1998) and Inagaki & Kanda (2008).

In conventional experimental studies of turbulence, turbulence component is usually defined as the residuals from the temporal average if the data are based on a single point measurement,

\[ \phi = \bar{\phi} + \phi' \],

where \( \phi \) is a physical variable, such as the velocity component or temperature. The over bar and the prime indicate the temporal mean and fluctuation terms, respectively. Hereafter, this conventional definition of fluctuation is called ‘TD’. TD generally involves both active and inactive fluctuation components if the averaging time is larger than the time scale of the inactive motion.

We use an instantaneous moving average in space to separate the low-frequency inactive motion

\[ \phi = [\phi_m] + \phi_m' \],

where the square brackets and prime with subscript \( m \) indicate the mean part of the moving average and residual fluctuation part, respectively. If the area for the moving average is sufficiently larger than the size of the active turbulence and sufficiently smaller than the size of the inactive motions, then the inactive motions can be approximated by the mean part of Eq. (2).

In the present study, the area average is constituted from the line average along the spanwise direction since it is still difficult to measure area averages in outdoor experiments. The validity of this method is discussed below.

3. Experimental setup

3.1. COSMO

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 Kanda et al. (2007) and Inagaki & Kanda (2008). The mean wind direction was usually from the northwest during the experiments in this study.

The mean flow characteristics at COSMO are also described by Inagaki & Kanda (2008). In general, the mean flow statistics are horizontally homogeneous, independent of the individual roughness cubes, at a height of 2H. The Reynolds stress is nearly constant, and the mean velocity changes logarithmically in the vertical direction around 2H. Therefore, a measurement of the horizontal distribution of the turbulence was conducted at 2H where the logarithmic region develops.

3.2. Experimental settings

In this study, the sonic anemometers were aligned horizontally at a constant height. The velocity and temperature fluctuations were measured at each location in sync. When the horizontal mean wind crosses this line, we obtained a horizontal-2D distribution of the velocity and temperature fluctuations by assuming Taylor’s frozen turbulence hypothesis in the streamwise direction, and by direct measurement along the row of instruments. Based on this strategy, we used the following two instrument configurations.

In configuration ‘C1’, the 10 sets of Kaijo DA600 (TR-90AH) anemometers were aligned horizontally and parallel to the NE–SW axis at a constant height of 3.0 m from the ground as indicated in Figure 1. The probe heads of the anemometers were directed northwest because this study addresses only flow coming from this direction. The measurement points were spaced at a uniform 1.5-m distance. Therefore, the horizontal distribution of the measurement points ranges up to 13.5 m in the spanwise direction. The datasets were collected in sync at 50 Hz using a TEAC LX10 data logger.

In the second configuration, ‘C2’, we used Young Model 81000 anemometers. Two sets of 15 Model 81000 devices were placed in 42-m straight lines along the NE–SW axis at the upwind and downwind sides of COSMO, as shown in Figure 1. The instruments were spaced at uniform 3-m intervals. The upwind and downwind rows were 84 m apart. All measured parameters, i.e., 30 sets of 3D velocity and temperature data, were collected in sync at a sampling rate of 10 Hz using a Chino KE3000 data logger.

4. Results

4.1. Spectral characteristics

Figure 2 shows the ensemble averages of the turbulent velocity spectra ($u'$, $v'$, $w'$) and the Reynolds stress cospectra ($\overline{u'w'}$) derived from TD and SD using different sizes of area $\Delta$ for moving average. These spectra were calculated using fast Fourier transforms. The frequencies were converted to wavenumbers ($f/U$) assuming the frozen turbulence hypothesis. The spectral densities and wavenumbers were normalized by the inner-layer variables $\overline{u^2}$ and $\overline{\epsilon}$, respectively. The value of $\overline{u^2}$ is estimated from the root mean of $\overline{u'w'}$ at 2H, as used by Inagaki & Kanda (2008). The shapes of the spectra of TD are well consistent with those of Kaimal et al.
Figure 2 Turbulent velocity spectra and Reynolds stress cospectra. These are the spectra of (a) Streamwise velocity, (b) spanwise velocity, (c) vertical velocity and (d) Reynolds stress. The solid line indicate the spectra of TD and the thin lines are those of SD for different sizes of $\Delta$.

(1972) except the low frequency parts of $u$ and $v$ spectra (not shown).

For all of spectra and cospectra, the spectral densities of SD became smaller than those of TD at the entire frequency range. The spectral energy at the lower frequencies was effectively reduced by subtracting the moving averaged components, although they are still not zero. With increasing the area for moving average $\Delta$, the shapes of spectra of SD reduce to those of TD. When the size of $\Delta$ is 9H, the entire shape of the $w$ spectra and $uw$ cospectra of SD are almost consistent with those of TD. However, the spectral shapes of $u$ and $v$ of SD at the lower frequency range still have considerable deficit from the TD spectra. This means that the low frequency motion, which is estimated from the moving average of the horizontal velocity along the spanwise direction, was nearly ‘inactive’ to the Reynolds stress and the extracted fluctuation of SD represents the active motion.

4.2. Horizontal distribution of the velocity fluctuations

A single 30-min dataset for the C2 configuration was extracted to visualize the horizontal distribution of $u$ over the entire COSMO domain. In this period, the horizontal mean velocity was 5.0 m s$^{-1}$ from the northwest at the measurement level, and the deviation of the mean wind direction was less than 1° from the NW–SE street axis. The flow is near-neutrally stratified ($z'/L = -0.0015$).

Figure 3 shows the horizontal distribution of $u$ of TD and SD observed at the downwind side of COSMO (‘C2 (Back)’ in Figure 1). The size of the visualized field extends 9 min in time, which is comparable to about 2700 m (1800H) in the streamwise direction if we assume the frozen turbulence hypothesis, and 42 m (14H) in the spanwise direction. The figures were folded every 3 min to keep the aspect ratio and to facilitate visualization.

The figure of the $u$-distribution of TD included a very large scale motion extended about a few minutes in the streamwise direction and covered the entire spanwise domain of COSMO (e.g. last 3 minutes are almost entirely negative values).

In contrast, the low-frequency motions seen in the $u$-distribution of TD disappeared in the distribution of SD. Instead, streaky structures of low momentum region clearly appeared in the $u$-distribution of SD. This type of structure has been observed in the logarithmic layers during various field and numerical experiments, e.g., Tomkins & Adrian (2003) and Hutchins & Marusic (2007) for flat walls in laboratory and atmosphere experiments, Watanabe (2004) and Kanda et al. (2006) for vegetations and cubic arrays in numerical simulations. Therefore, this is expected to be a universal characteristic of surface-layer turbulence regardless of the types of roughness. Considering these results and their spectra, the very large structure of the elongated low momentum region is expected to be a part of the active motion since it is found in the $u$-distribution of SD. The inactive motion within the atmospheric surface layer is attributed to the mixed layer convection passing over the experimental domain in COSMO and propagated to the horizontal velocity fluctuation within the surface layer.
5. Conclusions

The study suggests a method to separate the active and inactive motions using the spatial moving average in the spanwise direction. This method is validated using the datasets obtained in the outdoor reduced urban model. This resulted in a reduced major part of the horizontal velocity spectra at low frequency region by subtracting the moving averaged components, while preserving the entire Reynolds stress cospectra. Therefore, inactive motion, which is included in the horizontal velocity fluctuations, and active motion could be separated.

The horizontal distribution of the active motion included the very large scale motion of the elongated low momentum region, as found in various wind tunnel and atmospheric field experiments, and numerical simulations of near wall turbulence. Therefore, this structure is expected to be a universal characteristic of active motion over wall bounded turbulence.

References


