5.2 EVALUATION OF THE INNER-SCALING SIMILARITY OF TURBULENCE OVER URBAN-LIKE ROUGHNESS DERIVED FROM AN OUTDOOR SCALE MODEL EXPERIMENT

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## 1. INTRODUCTION

It is well-known that the turbulent characteristics within the atmospheric surface layer are expressed by universal functions of the inner-scaling parameters (e.g. Monin-Obukhov similarity). Although the universal relations between the turbulent statistics and the inner-scaling parameters have been confirmed in flat and horizontally homogeneous fields, it is not obvious that these relations are applicable for urban surface layers since the inner-scaling parameters depend on surface conditions.

The inner-scaling similarity of the turbulent characteristics within the surface layer was evaluated over the array of massive obstacles, mainly focusing on the impact of the roughness. For this purpose, turbulence was measured in the facility of comprehensive outdoor scale model experiment for urban climate (COSMO, the photograph is in Fig. 1).

This study focuses on two main characteristics of the COSMO experimental site: 1) the building array is composed of cubes of uniform shape and material, which are regularly arranged over a flat plate; 2) the experiment was conducted within the atmospheric boundary layer. Experimental uncertainties that come with urban experiments, such as irregular arrangement of buildings, complexities of land use and the influence of human activities, were eliminated so as to simplify the evaluation of the effects of roughness on the inner-scaled turbulent statistics under atmospheric conditions.

## 2. OUTDOOR SCALE MODEL EXPERIMENT

### 2.1 *COSMO*

COSMO experimental facility was constructed in Nippon Institute of Technology, Saitama, Japan. The upwind fetch is opened to the reaped rice field which succeeds about 500 m upwind direction. The model is composed of a flat rectangular plate in the basement and 512 square cubes on it. The plate and blocks are made of concrete. The size of the plate is 50 m by 100 m in horizontal extent. The square cubes are 1.5 m (=H) on a side, which is about 1/5 scale of the typical residential buildings in Japan. The cubes are arranged regularly as the plan area index becomes 0.25. Three 8-meter meteorological towers are built at the north-west, centre, and south-east in the site. The schematic of this experimental site is shown in Fig. 2.

### 2.2 *Instruments*

To observe the turbulent properties, we used 5 Kaijo sonic anemometer-thermometers (DA-600 TR90AH probe). The streamwise, spanwise, vertical velocity ($u$, $v$, $w$) and also the temperature ($T$) are measured at 50 Hz sampling rate. The instruments are equipped on the center tower at the heights of 4H, 3H, 2H, 1.5H and H.

### 2.3 *Data acquisition and qualification*

The measurement was conducted for about 2 months in winter. The temporal mean statistics and turbulent spectra and cospectra were calculated in every 30 minutes of this measurement period.

For the quality control, the data obtained in the rain were excluded. The range of the mean wind speed is selected from 1 m $s^{-1}$ to 3 m $s^{-1}$ at 2H. The flows come from between the North-West street axis and the 45 degree apart to the south-west direction are used for the analysis to avoid the flow distortion. Since the linear detrending was not applied, the data which have large divergences during the averaging period are excluded to secure the steady flow.

The present study concerns the turbulent flow under neutral stratification. The atmospheric stability was calculated as,

$$\frac{z'}{L} = -\frac{(g/T)(\overline{w'T'})}{u_*^3/kz'} \,. \qquad (1)$$

Fig. 1 Photograph of COSMO experimental facility.

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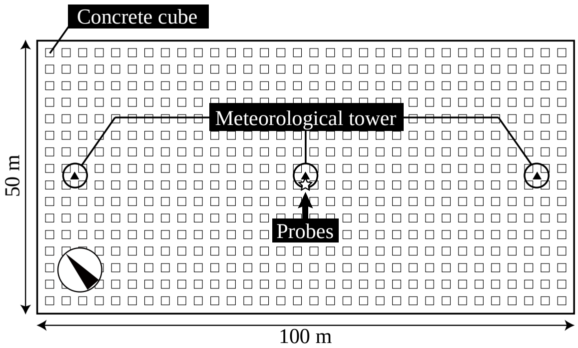


Fig. 2 Schematic of COSMO experimental site.

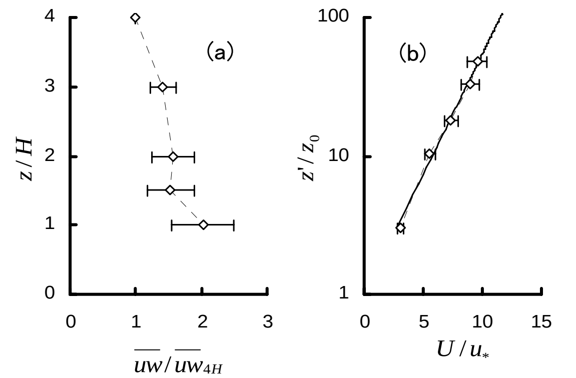


Fig. 3 Vertical variations of the momentum flux and the mean velocity.

Where $L$ is Obukhov length (m), $z'$ is the effective height defined as $z' = z - d$ where $z$ is the measurement height and $d$ is the displacement height (m). $g$ is the gravity acceleration (m s$^{-2}$), $u_*$ is friction velocity (m s$^{-1}$), $k$ is von Karman constant ($k = 0.4$ is applied). The over bar and the prime means the temporal average and the fluctuating component. In the present study, the stability range of the neutral stratification is specified as $|z'/L| < 0.05$.

## 3. MEAN FLOW CHARACTERISTICS

Fig. 3a shows the vertical distributions of the Reynolds stress normalized by the value at 4H, and of the mean wind velocity. The Reynolds stress around 2H is nearly constant. The horizontal distribution of the mean flow characteristics around the obstacle converges to a constant up to 2H (not shown). Therefore the height 2H is expected above the roughness sublayer. The friction velocity is calculated from the Reynolds stress obtained at 2H, such as $u_* = (-\overline{u'w'})^{1/2}$.

The values of $d$ and the roughness length $z_0$ in COSMO were estimated assuming the logarithmic variation of $U/u_*$ under neutral stratification. Then, $d = 1.2$ m (0.8H) and $z_0 = 0.1$ m (0.07H) were derived.

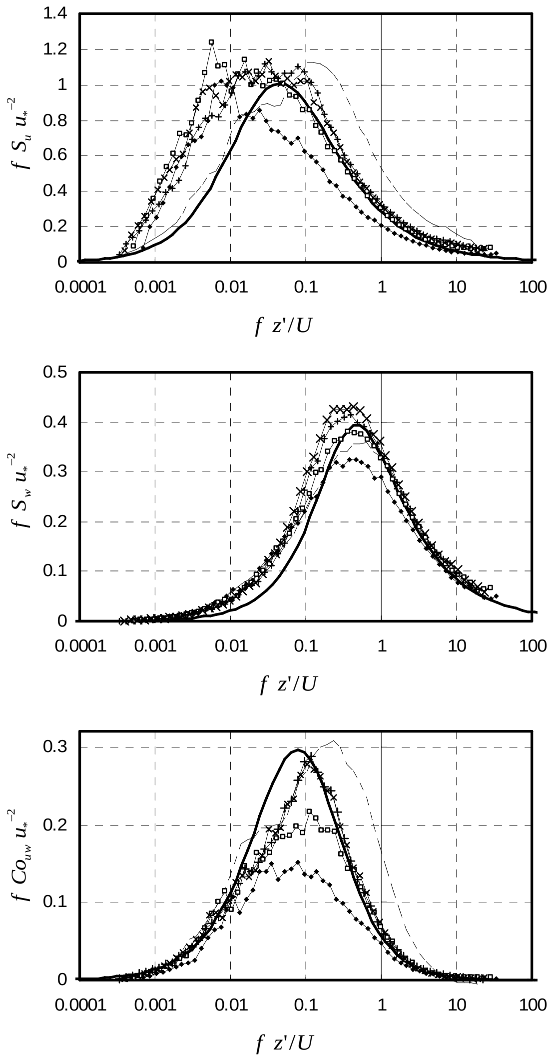


Fig. 4 Pre-multiplied spectra and cospectra for different heights.

These values are similar with the values obtained in a wind tunnel experiment (Cheng & Castro 2002). The $U/u_*$ in COSMO corresponds well with the urban reference (Fig. 3b).

## 4. RESULTS

### 4.1 *Spectra and cospectra*

The spectral similarity of the turbulent flow was evaluated. The turbulent spectra and cospectra were calculated using Fast-Fourier-Transform (FFT). The raw frequency $f$ was converted to wavenumber by using Taylor's frozen hypothesis with local mean velocity at each effective height. The spectra $S_u$, $S_w$, $Co_{uw}$, and the wavenumber are normalized by inner-scaling parameters, such as $S_u u_*^{-2}$, $S_w u_*^{-2}$, $Co_{uw} u_*^{-2}$ and $f z'/U$. These spectra and cospectra were ensemble averaged.

The ensemble average of these spectra and cospectra of the pre-multiplied form are plotted on the log-linear axes together with the rural reference provided by Kaimal et al. (1972).

Those values within the constant-stress layer (2H) collapsed well in the corresponding rural reference in the high frequency part. In the lower frequency part, $f\,S_u\,u_*^{-2}$ (and also $f\,S_w\,u_*^{-2}$ slightly) were apart from the reference curve. The values of $f\,Co_{uw}\,u_*^{-2}$ generally agree well with the referenced curve over the all wavenumber range.

The collapse of the similarity in the low frequency region is due to the outer-layer disturbance above the inertial layer, which would be attributed to the ABL mixing. The ABL mixing depends not only on the surface conditions which are represented by the inner-scaling parameters but more on the synoptic conditions (Stull 1988). Therefore, it does not follow the inner-scaling regime.

Even so, the universality of each spectra in the high frequency regions or the cospectra in the whole frequency regions is a strongly evidenced that the inner scale similarity is true. Such a fine scale or active eddies are self-similar irrespective of the surface conditions or also of the outer-layer conditions.

### 4.2 *Non-dimensional velocity fluctuation*

Next we consider the standard deviation of the velocity fluctuations with inner-scaling, which are $\sigma_u = \overline{u'}^{1/2}$ and $\sigma_w = \overline{w'}^{1/2}$. In Fig. 5, the values of $\sigma_u/u_*$ and $\sigma_w/u_*$ in COSMO are plotted on $z'/z_0$ together with the urban reference provided by Roth (2000). There is a peak value of both $\sigma_u/u_*$ and $\sigma_w/u_*$ within the constant-stress region (near 2H) as similar to the wind tunnel experiments (Raupach et al. 1980, Cheng & Castro 2002) although the magnitudes of the values are larger than them. In comparison with the urban reference, the value of $\sigma_u/u_*$, and $\sigma_w/u_*$ slightly, at 2H in COSMO is larger than the urban average.

Panofsky et al. (1978) indicated that the value of $\sigma_u/u_*$ depends on the ABL mixing scale. This has also observed in urban experiments (e.g. Clarke et al. 1982, Rotach 1993), whose studies used the peak frequency of the horizontal velocity spectra $f_{u\,peak}$ to represent the ABL mixing scale. Fig. 6 shows the values of $\sigma_u/u_*$, and $\sigma_w/u_*$ obtained at 2H in COSMO plotted on the value $f'_{u\,peak} = f_{u\,peak} z'/U$. As observed in the former experiments, the value of $\sigma_u/u_*$ decreased with increasing $f'_{u\,peak}$. The value of $\sigma_w/u_*$ was mostly insensitive to $f'_{u\,peak}$.

In the other aspect of the non-dimensional velocity fluctuations, Clarke et al. (1982) indicated that the values of $\sigma_u/u_*$ and $\sigma_w/u_*$ decreases with

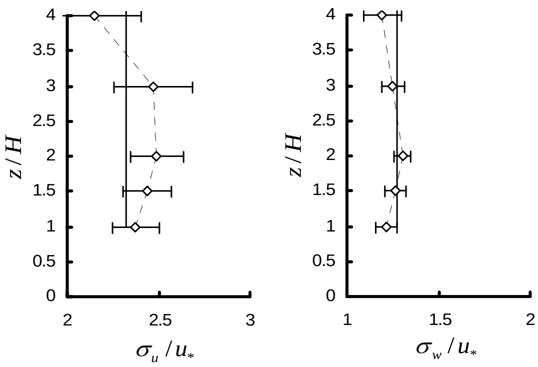


Fig. 5 Vertical variations of non-dimensional velocity fluctuations.

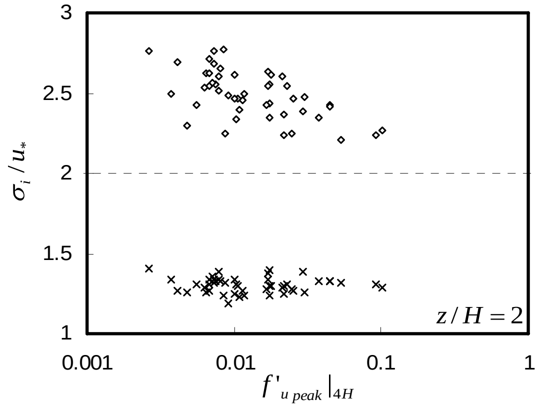


Fig. 6 Non-dimensional velocity fluctuations plotted on the peak frequencies of u-spectra at 4H.

increasing $z_0$. If it is true, it can account for the difference of the inner-scaled values in between COSMO and cities. Therefore it is reevaluated.

The data in COSMO is useful in this evaluation since it can provide the value of the very small $z_0$. In addition, the data in rural experiment (Högström 1990) and also wind tunnel experiments (Raupach 1981) are compared with the COSMO and urban experimental values (Roth 2000, Clarke et al. 1982, Yersel and Goble 1986). Then it has to be take care that the velocity fluctuation can affected by the ABL mixing. Therefore, the non-dimensional index $z_0/z_i$ was used instead of $z_0$ to intercompare the datasets obtained in various experiments.

The value of $z_i$ in COSMO is estimated from $f_{u\,peak}$ at 4H, such as $z_i = 1.5\,U/f_{u\,peak}$ (Kaimal et al. 1976). The values in urban experiments are specified to a constant value of 500 m. This very rough estimation is not so significant in the present comparison because the values of $z_i$ in COSMO and cities are both several hundreds of meters although their values of $z_0$ are orderly different.

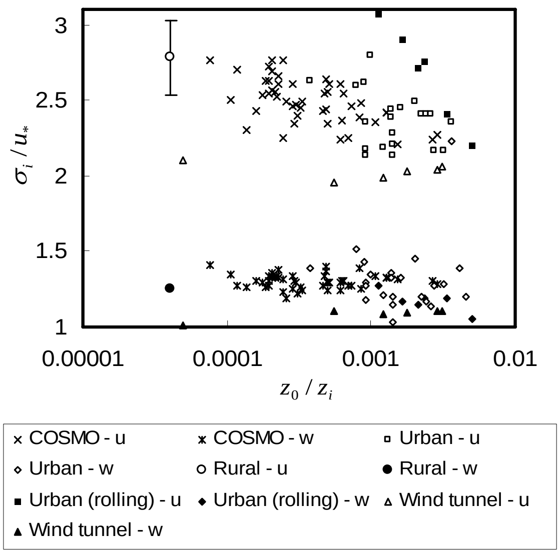


Fig. 7 Variation of the non-dimensional velocity fluctuations for the different roughness length normalized by the outer-layer scale.

Fig. 7 shows the $\sigma_u / u_*$ and $\sigma_w / u_*$ obtained from various data sources plotted on $z_0 / z_i$. The values of $\sigma_u / u_*$ slightly decrease with increasing $z_0 / z_i$ for COSMO and field observations. Meanwhile, the value in the wind tunnel experiments becomes the lower limit that is about 2.0, and the value of the urban (rolling terrain) are exceptionally larger than the other experimental values.

The index $z_0 / z_i$ means the relative contribution of the inner- and outer-layer disturbance on the inner-scaled turbulent characteristics. Basically, the existence of the outer-layer disturbance increases the value of velocity fluctuation. Then, the relative contribution of the outer-layer disturbance to that of the surface induced fluctuation changes depending on the roughness and also outer condition.

The smaller value of $\sigma_u / u_*$ in the wind tunnel experiments are probably because no prominent outer-layer disturbance is generated in the wind tunnel experiments even for very small values of $z_0 / z_i$. The values in the rolling terrain were obtained in the rolling terrain. Raupach et al. (1991) also reviewed that $\sigma_u / u_*$ above rolling terrain is similarly large (more than 3.0). Probably, the topographical variation induced mechanically an additional ABL scale turbulent mixing (Stull 1988), resulting in the enhancement of the outer-layer disturbance. Even so, the value of $\sigma_w / u_*$ does not change so much with $z_0 / z_i$.

## 5. CONCLUSIONS

The results of the present study illustrated that the inner-scaling similarity was valid for vertical velocity fluctuations and the momentum transfer in the COSMO site, which are consistent with the values observed from a flat and homogeneous field. However, the similarity does not work well for horizontal velocity fluctuations.

This failure of the inner-scaling similarity for the horizontal velocity fluctuation is attributed to the outer layer disturbance, which imposes on the horizontal velocity fluctuation, but not to difference of roughness. The relative contribution of the outer-layer disturbance to modify the inner-scaled velocity fluctuation changed in different roughness.

## ACKNOWLEDGEMENTS

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