Nature of Streaky Structures Observed with a Doppler Lidar

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Abstract Observations using a three-dimensional scanning coherent Doppler lidar in an urban area revealed the characteristics of streaky structures above a rough, inhomogeneous surface for a high-Reynolds-number flow. The study focused on two points: (1) the frequency of occurrence and conditions required for the presence of streaky structures, and (2) the universal scaling of the spacing of streaky structures (λ). The horizontal snapshots of the radial velocity were visually classified into six groups: Streak, Mixed, Fishnet, No streak, Front, and Others. The Streak category accounted for more than 50% of all possible flows and occurred when the horizontal wind speed was large and the atmospheric stratification was near-neutral. The spacing (λ) was estimated from the power spectral density of the streamwise velocity fluctuations along the spanwise direction. The spacing λ decreased with an increase in the local velocity gradient. Furthermore, it was revealed that the local velocity gradient normalized by the friction velocity and the boundary-layer height (z_i) comprehensively predicts λ/z_i under various experimental and environmental conditions, in terms of the scale of motion (i.e., indoor and outdoor scales), thermal stratification (i.e., from weakly unstable to stable stratification), and surface roughness (i.e., from flat to very rough surfaces).

Keywords Doppler lidar • Roll vortices • Spacing of streaky structures • Streak

1 Introduction

We investigate streaky structures within the urban surface layer observed by a three-dimensional scanning coherent Doppler lidar. Although roll vortices and streaks have similar streaky patterns along the streamwise direction, they are explicitly distinguished in terms of the driving force: roll vortices require buoyancy whereas streaks do not. Roll vortices have largely been observed within the mixed layer due to the deformation of the Bénard cell convection by vertical shear and have been examined via numerical simulations (Deardorff 1972; Sykes and Henn 1989), aircraft observations (Grossman 1982; Müller et al. 1999), and satellite photographs (Walter 1980).

In contrast, streaks, mainly investigated in the field of fluid dynamics, are considered to be packets of hairpin vortices within the neutral boundary layer (Adrian et al. 2001). Hairpin vortices are stretched along the streamwise direction by wind shear associated with the mean velocity gradient (Zhou et al. 1999). Recently, streaks within the atmospheric boundary layer (ABL) have been reported (Drobinski and Foster 2003; Drobinski et al. 2004; Hutchins and Marusic 2007; Inagaki and Kanda 2010), and a large-eddy simulation (LES) study of Drobinski and Foster (2003) demonstrated that streaks contribute to the maintenance of surface stress and momentum flux.

Past studies have indicated that streaks and roll vortices in the outer layer affect the turbulence near the surface. Hutchins and Marusic (2007) found large streaky structures with low- and high-speed regions in the logarithmic and lower wake regions above a flat surface under neutral stratification, which were termed “superstructures”. The superstructures were not merely superimposed as a low-wavenumber mean shift into the near-wall region, but rather appeared to actively modulate the production of near-wall scales. Similar “superstructure”-type coherent structures (Hutchins and Marusic 2007) have been observed over very rough surfaces in an outdoor urban-scaled model experiment (Inagaki and Kanda 2010) and a wind-tunnel experiment (Takimoto et al. 2013). Intermittent strong upward motion from the cavity, termed “flushing”, frequently occurs when low-speed streaks pass above the canopy (Inagaki et al. 2012; Takimoto et al. 2013). In weakly unstable stratification, roll vortices coexist with streaks (Moeng and Sullivan 1994; Khanna and Brasseur 1998; Castillo et al. 2011), in which roll vortices affect the locations of ejections and sweeps associated with streaks in the surface layer (Khanna and Brasseur 1998; Castillo et al. 2011). For the modelling of turbulent fluctuations near the surface, the temporal (spatial) distribution of the velocity of roll vortices and streaks is important. Marusic et al. (2010) and Mathis et al. (2011) proposed a mathematical model to predict near-wall turbulence, given only large-scale information related to streaks from the outer layer.

Coherent turbulent structures within the ABL have been visualized by remote sensors, which can resolve the instantaneous image of turbulent structures within the ABL over several kilometres. The understanding of the spatial characteristic of flow fields has been improved by recent pioneering studies. For example, Weckwerth et al. (1997) conducted radar observations in east-central Florida and analyzed the environmental conditions under which several types of turbulent patterns are likely to occur. In addition, the spatial characteristics of roll vortices (e.g., wavelength and direction of roll vortices) were quantified using 13 cases. Doppler lidar has been used widely to investigate coherent turbulences within the ABL (Drobinski et al. 1998, 2004;

Newsom et al. 2008; Iwai et al. 2008; Fujiyoshi et al. 2009; Fujiwara et al. 2011) because it is the only tool that can directly observe the spatial snapshots of streaky structures in the ABL. Träumner et al. (2015) made an observations using a dual-Doppler lidar technique in a rural area, with the observed flow fields visually classified into four groups, and the streamwise and spanwise integral scales of coherent structures are investigated.

The observations of streaky structures in an urbanized area are important for the following two reasons: first, from a scientific perspective, the urban boundary-layer flow has a high Reynolds number over a rough and inhomogeneous surface, which cannot be reproduced in the wind tunnel. Therefore, observations of the urban boundary layer have the potential to improve our understanding of the turbulent boundary layer. Second, from the perspective of urban air quality, it has been observed that streaky structures develop not only above a flat surface in indoor experiments but also above the very rough surface of the urban boundary layer (Drobinski et al. 1998; Newsom et al. 2008; Fujiyoshi et al. 2009). In addition, LES described by Inagaki et al. (2012) demonstrated that the streaky structures in the surface layer are coupled with "flushing" events, suggesting that the ventilation in the urban area is strongly affected by the streaky structures. To assess the diffusion of air pollution, moisture, and heat within the building canopy, it is desirable to clearly understand the nature and characteristics of streaky structures in the urban surface layer. However, to date, only a few long-term Doppler lidar investigations of urban environments have been performed.

In this study, we investigate streaky structures, including roll vortices and streaks, within the urban boundary layer. Specifically, we determine atmospheric conditions under which streaky structures appear, and quantify their spacing, λ. We conducted a three-month investigation (from 25 September 2012 to 31 December 2012) using a Doppler lidar, a sonic anemometer, and a multi-weather sensor in the urbanized area of Tokyo, Japan. We sampled various kinds of flow fields: coherent flows (e.g., Bénard cell convection, roll vortices, and streaks) and non-coherent flows. Through the classification of all possible flow patterns, the atmospheric conditions required for the occurrence of streaky structures were clearly specified. The spacing λ was quantified and then comprehensively examined in a non-dimensional approach, with reference to previous LES and wind-tunnel experiments.

2 Instrumentation

A Doppler lidar was used to measure the spatial velocity distribution, and a weather station and sonic anemometer used for supplementary monitoring of the flow environment, as shown in Fig. 1a. The specifications and roles of each instrument are described below. The Doppler lidar system (a three-dimensional scanning coherent Doppler lidar, LR-02A, Mitsubishi Electric Co., Tokyo, Japan) was installed on the rooftop of a building at the Tokyo Institute of Technology, Tokyo, Japan at a height of 55 m above the ground. The Doppler lidar was operated at a wavelength of 1.54 μm with a pulse repetition frequency of 4000 Hz, the laser pulse energy and laser pulse width were 0.5 mJ per pulse and 213 ± 10 ns, respectively. The detection range was from 325 m to 4275 m, with a range resolution of 50 m in the radial direction. The radial velocity and signal-to-noise ratio (SNR) were obtained by averaging 1000 pulses. Plan Position Indicator (PPI) and Range Height Indicator (RHI) scans were conducted at scan speed of 4.5 ° s^{-1} and 5.1 ° s^{-1}, respectively. The azimuth resolutions of PPI and RHI scans were 1.1 ° and 1.2 °, which were determined using the pulse repetition frequency, the number of averaged pulses, and the scan speed. The Doppler lidar repeatedly conducted a 30-min scan sequence, which included seven PPI scans at the elevation angle of zero, seven RHI scans with an azimuth of 135 °, and two RHI scans with an azimuth of 45 °, which were orthogonal to other RHI scans (Table 1).

A weather station (WXT520 weather transmitter, Vaisala Co., Vantaa, Finland) was installed at the same location as the Doppler lidar, and monitored rain intensity, wind speed, wind direction, air temperature, pressure, and relative humidity. In our analysis, the rain intensity was used to identify and remove observations made during rain. A sonic anemometer (CYG81000, R. M. Young Co., Traverse City, MI, USA) was installed on the rooftop of a building at a height of 25 m above the ground, located 500 m north-west of the Doppler lidar. Three wind-velocity components and air temperature were recorded using a data logger (GL220, Graphtec Co., Tokyo, Japan), with a sampling rate of 10 Hz, and sonic anemometer measurements used to obtain turbulence statistics, as shown in Sect. 3.4.

The Doppler lidar measurement was compared with that of the sonic anemometer in terms of the horizontal wind speed; the relationship was linear, with a correlation coefficient of 0.84. The wind speed measured by Doppler lidar was 2.2 times greater than that measured by the sonic anemometer due to the difference in the measurement height. Apart from the accuracy limitations of the instruments, possible reasons for the discrepancy between these measurements are, (1) the observation height of the Doppler lidar was 30 m higher than that of the sonic anemometer, and (2) the estimated value from the Doppler lidar measurement represented the spatially-averaged wind velocity within a 2025 m radius, while the sonic anemometer provided a point observation.

3 Methodology

3.1 Visual Classification of Flow Patterns

Past studies have visually classified the flow pattern within the ABL and have attempted to classify the flow pattern inductively based on atmospheric variables. Observations of the flight performance of gulls above the sea by Woodcock (1975) showed that the presence of cell-like ascending convective motions is related to wind speed and air temperature differences between the sea and atmosphere. Aircraft observations above the sea by Grossman (1982) indicated that roll vortices and random cells can be categorized according to the atmospheric stability expressed by the ratio of the sub-cloud-layer height to the Obukhov length. A LES study by Sykes and Henn (1989) demonstrated that the ratio of the friction velocity to the convective velocity is an important parameter that can be used to determine the formation of roll vortices. These studies have focused on the occurrence conditions of coherent flow fields based on knowledge of convective flow dynamics. Träumner et al. (2015) visually classified the flow pattern into coherent, periodic, and homogeneous patterns; the homogeneous pattern does not include clear characteristic structures in the flow and is a complementary class to the previous classifications. Here, we also visually classified the pattern of radial velocity distributions into six groups as detailed below.

Horizontal snapshots of each flow pattern were visually classified into six categories: Streak, Mixed, Fishnet, No streak, Front, and Others. Figure 2 and Table 2 show horizontal snapshots of each group and the criteria used for the visual classification. We used three indices for the visual classification, the first of which was the convergence line. On passage of a cold front, a clear convergence line could be seen (e.g., Fig. 2e). The second index was the shape of the boundary between positive and negative radial velocities; if the boundary was a straight line, e.g., the categories Streak (Fig. 2a) and No streak (Fig. 2d), wind direction was considered to be almost homogeneous. The third index was the homogeneity of the spatial pattern of radial velocity, as seen in the categories Streak, Mixed (Fig. 2b), and Fishnet (Fig. 2c). The categories Streak and Mixed had a streaky pattern, and the category Fishnet had a cell-like pattern (Fujiwara et al. 2011). The distinction between the categories Streak and Mixed was made using the second index, with the boundaries of positive and negative radial velocities being a straight line for the category Streak and a wave-like line for the category Mixed. The category No streak was a one-directional flow, without any specific coherent structures. The category Front (Fig. 2e) had a clear convergence line within the observational area. The category Others (Fig. 2f–l) had neither a streaky nor a cell-like pattern, with a distorted boundary between positive and negative radial velocities. For example, the flow with low wind speed during nighttime and the flow with gravity waves were included in the category Others. Although the category Others in Fig. 2f resembled the category Mixed in Fig. 2b, in terms of the shape of the boundary between the positive and negative radial velocities, it can be categorized differently because the category Mixed in this case had streaky patterns along the wind direction, while the category Others did not. It is noted that the objectivity of these visual classifications was evaluated using statistical parameters, which simplified the visual criteria as shown in Appendix 1.

We did not classify snapshots, which included many errors, i.e., the categories Rain and Error; the category Rain corresponded to snapshots during rain, which were observed by the weather station. The category Error corresponded to snapshots whose error percentage for the 2025-m radius was larger than 10% without any precipitation. The judgement of error in each grid was made based on the SNR value.

3.2 Vertical Distribution of Horizontal Wind Speed

The vertical distribution of horizontal wind speed was calculated using two orthogonal RHI scans (No. 2 and No. 3 in Table 1) as follows,

$$U_{ew}(z) = -\overline{v_{r1}(r, \theta_{el})/\cos\theta_{el}} \sin\theta_{az1} + \overline{v_{r2}(r, \theta_{el})/\cos\theta_{el}} \cos\theta_{az2}, \quad (1)$$

$$U_{ns}(z) = \overline{v_{r1}(r, \theta_{el})/\cos\theta_{el}} \cos\theta_{az1} + \overline{v_{r2}(r, \theta_{el})/\cos\theta_{el}} \sin\theta_{az2}, \quad (2)$$

where U_{ew} and U_{ns} are the east-west and the north-south velocity components, respectively, z is the height, v_r is the radial velocity, r is the radial distance, θ_{el} is the elevation, θ_{az} is the azimuth angle from the north, the over bar is the spatial average for each 50 m in height, and the subscripts (1 and 2) of v_r and θ_{az} correspond to the first and second scan. In this estimation, the contribution of vertical velocity to the radial velocity was neglected. Therefore, we used only v_r at lower elevations ($\theta_{el} < 60$ ° or 120 ° $< \theta_{el}$) where the contribution of vertical velocity was sufficiently small. The horizontal velocity and wind direction were calculated from U_{ew} and U_{ns}. This mean wind profile was used to obtain the boundary-layer height (z_i) and the velocity gradient ($\Delta U/\Delta z$).

3.3 Boundary-layer Height

The boundary-layer height z_i was estimated using the vertical profile of the SNR and the wind profile estimated in Sect. 3.2. Three different physical boundaries were used to determine z_i, the boundary of aerosol density, the cloud base, and the prominent maximum peak of the horizontal wind speed. First, we estimated the boundary of aerosol density and the cloud base using the SNR, which decreased at the top of the ABL (Figs. 3a, c) and abruptly increased at the cloud base (Figs. 3b, d). The decrease in SNR at the top of the ABL and the increase at the cloud base (Barlow et al. 2011) were extracted using the Haar wavelet (Cohn and Angevine 2000). Figure 3c and d shows the calculated Haar-wavelet coefficient of the averaged SNR profile of five vertical scans observed for 30 min. From the peak of the Haar coefficient, the boundary of aerosol density and the cloud base were extracted as z_i. If the horizontal wind speed had a positive peak (boundary between positive and negative wind velocity gradient) below z_i, which was first defined by the Haar-wavelet coefficient, then z_i was redefined by the peak of horizontal wind speed (Fig. 3e, f).

3.4 Turbulence Statistics

Turbulence statistics were calculated using the wind velocity and air temperature, which were measured by the sonic anemometer, as follows,

$$u_* = \sqrt{-\overline{u'w'}}, \tag{3}$$

$$T_* = -\overline{w'T'}/u_*, \tag{4}$$

$$L = (k\,(g/T)T_*)/u_*^2, \tag{5}$$

where u is the streamwise velocity component, w is the vertical velocity, T is the air temperature, u_* is the friction velocity, T_* is the air temperature scale, L is the Obukhov length, k is the von Kármán constant (0.4), and g is the acceleration due to gravity (9.8 m s^{-1}). The over bar and the prime are the temporal averages for 30 min and the fluctuation from the averaged value, respectively.

3.5 Spacing of Streaky Structures

The spacing λ was estimated from the power spectral density of the streamwise velocity component fluctuation ($\widetilde{u'}$) along the spanwise direction. First, $\widetilde{u'}$ was estimated from the radial velocity as follows,

$$v_r'(r,\theta) = v_r(r,\theta) - \overline{v_r(r,\theta)}, \quad (6)$$

$$\widetilde{u'}(r,\theta) = v_r'(r,\theta)/\cos\theta, \quad (7)$$

where r is the radial distance, θ is the azimuth angle from the wind direction, v_r is the radial velocity, which was observed by PPI scans at the elevation angle of zero, v_r' is the radial velocity fluctuation, and $\overline{v_r}$ is the radial velocity component of the spatial mean horizontal velocity, which was estimated using the velocity azimuth display method (Browning and Wexler 1968). The coordinate of $\widetilde{u'}$ was transformed from the original polar coordinate (50 m × 1.1 °) to the rectangular coordinate (50 × 50 m). The power spectral density was calculated along the spanwise direction, and the spacing λ was determined from the peak of the power spectral density, and the 30-min averaged spacing λ was used in the results.

The estimation of $\widetilde{u'}$ in Eqs. 6 and 7 is applicable for the cases of homogeneous wind direction, such as the category Streak (Fig. 2a), but not for inhomogeneous wind directions such as the categories Front (Fig. 2e) and Others (Fig. 2f-l), although only the category Streak was the target of our analysis. In addition, the area for which θ is close to 90 ° cannot be used for the estimation of $\widetilde{u'}$ because the radial velocity predominantly consists of the spanwise component rather than the streamwise component with θ = 90 °. Therefore, the areas for analysis were selected as rectangles of 3200 m × 1000 m (Fig.

4). The orientation of the rectangular areas was set as x and y, the local coordinates of the rectangle, and was parallel to the streamwise and spanwise directions of the mean wind estimated by the velocity azimuth display method, respectively. The location of the rectangular areas was determined to avoid the deformation of estimated $\widetilde{u}'$ due to large θ and also to consider the azimuth resolution. The degree of deformation of $\widetilde{u}'$ was evaluated by comparing it with the distribution of the actual streamwise velocity fluctuation (u') based on an urban LES dataset, which simulated the flow field above the same urban geometry as the present experimental site (Huda et al. 2016). In the selected rectangular areas, the correlation coefficient of $\widetilde{u}'$ and u' was more than 0.9, and the deformation of $\widetilde{u}'$ did not significantly influence the estimation of the spacing λ. Although the azimuthal resolution became lower with distance in the radial direction, in the selected area it was smaller than the spatial resolution in the radial direction. Although there was a discontinuity in the radial velocity distribution at the line at the start and end of PPI scans (e.g., Fig. 2f), we confirmed that there were almost no difference in the estimated values with and without this discontinuous line in the rectangular areas, which are seen in the leeward or windward sides of the Doppler lidar in the same scan sequence.

The 30-min averaging time of the spacing λ was determined based on the spectral gap in the ABL that separated it from the synoptic variation (Stull 1988). Although it was also a concern that the spacing λ may be affected by the changing horizontal wind speed and the wind direction during the averaging time, we confirmed that there was almost no correlation between the spacing λ and the varying wind speed and wind direction during the averaging period, which was quantified as a standard deviation among the respective averaging times.

Figures 4c and d show the agreement of the estimated spacing λ and the visually expected spacing of streaky patterns of $\widetilde{u}'$ in two cases. In the later discussion, we cite the previous studies listed in Table 3. The previous studies (e.g., Lin et al. 1997; Takimoto et al. 2013) provided length scales determined at the point where a two-point correlation had the minimum peak, not the spacing λ estimated by the spectrum. We transformed the length scales into the spacing λ using the relationship of the length scale and the spacing λ mentioned in Appendix 2. It is noted that the relationships shown in Figs. 7–9 are robust, irrespective of the definition of the spanwise scale of the streaks, i.e., the minimum peak of a two-point correlation and the spectral peak used herein.

4 Results

4.1 Occurrence Condition of Flow Patterns

The occurrence frequencies of the flow patterns in autumn and winter were statistically examined; the category Streak dominates more than half of all possible flows in both seasons: 59% in autumn and 51% in winter. The rate of coherent flows, which includes the categories Streak, Mixed, and Fishnet, was 73% throughout the two seasons. This percentage was higher than that reported by Träumner et al. (2015), which was based on dual Doppler lidar observations above a rural area. In their results, coherent flow fields accounted for 53–65% of all flows. One possible reason for this difference between the two sites can be attributed to the influence of regional distributions, such as seasonal wind, local circulations, and mesofronts. Another possibility is the influence of surface conditions, in such a way that large vertical wind shear above an urbanized area is more readily associated with the category Streak than is the case above a rural area. In addition, it is relatively difficult to accomplish a stable stratification in an urban area due to the anthropogenic heat emission and large heat capacity of buildings (Clarke 1969), which decrease the frequency of occurrence of the category No streak, as explained below.

Träumner et al. (2015) clarified the diurnal variation in the frequency of occurrence of the two types of flow fields, with and without coherent structures, and showed that more than 70% of flow fields that contain structures appeared during daytime. Figure 5 shows the diurnal variation in the six flow patterns and in the average heat flux ($\overline{w'T'}$). Coherent flows (i.e., the categories Streak, Mixed, and Fishnet) have different tendencies in the number of occurrences; the category Streak appeares throughout the entire day, while in contrast, the categories Mixed and Fishnet mainly appear only during the daytime when $\overline{w'T'}$ is positive. The category No streak mostly appears at night when $\overline{w'T'}$ is negative. These results indicate that the heat flux is an important factor in explaining the occurrence condition of each flow pattern.

Figure 6 shows the relationship between horizontal wind speed U at the height of the Doppler lidar and the stability parameter $-z_i/L$ for each flow. The value of U was estimated by the velocity azimuth display method (Browning and Wexler 1968), and each plot used an averaged value for 30 min. In the cases of unstable stratification ($-z_i/L >$0, Fig. 6a), the boundary between the categories Fishnet and Mixed well matched the limit for random cells reported by Grossman (1982). Moreover, the boundary between the categories Mixed and Streak also matched the limit for roll vortices, proposed by Grossman (1982). Although $-z_i/L$ strongly affects the flow pattern, U is also an important parameter used to determine the occurrence condition of flow fields. In strongly unstable stratification ($-z_i/L >$20), the category Fishnet appeared for a smaller U than did the category Mixed. In weakly unstable stratification ($0< -z_i/L <5$), the categories No streak and Others occurred under a smaller U, and in stable stratification (Fig. 6b), the category Streak appeared in near-neutral conditions with a larger U, as expected. With more stable conditions, the share of the category Streak decreased, and non-coherent flow structures (i.e., the categories No streak and Others) emerged.

4.2 Spacing of Streaky Structures

This section analyzes the spacing of streaky structures under conditions of differing scales of motion, thermal stratification, and surface roughness. This is accomplished by compiling the measurements from various experiments and flow environments, reproduced by three additional experiments, which are listed in Table 3, and the present Doppler lidar measurements. Doppler-lidar observations are discriminated for three meteorological conditions; DL and DL_cloud cases observed under conditions with or without clouds at the top of the boundary layer, and a DL_typhoon case observed during typhoons. LES_flat and LES_city represent the results of LES for a flat surface (Lin et al. 1997) and real urban geometry (Huda et al. 2016) under neutral stratification, respectively. WT_cube represents the results of the wind-tunnel experiment for various surface geometries, including flat surface and three types of cubical arrays (Takimoto et al. 2013). These classes are used in Figs. 7–9.

Figure 7 shows the relationships between the spacing λ and meteorological variables such as the stability ($-z_i/L$), the horizontal wind speed (U), and the local velocity gradient ($\Delta U/\Delta z$); the last obtained from the vertical distribution of the horizontal wind speed, as mentioned in Sect. 3.2.

The dual-Doppler lidar observations described by Newsom et al. (2008) demonstrated that the spacing λ becomes smaller when conditions become more stable. Although the same trend is shown in Fig. 7a, plots that are near-neutral are scattered, suggesting that other parameters are required to determine the spacing λ under neutral stratification.

The velocity gradient may be a relevant parameter that affects the length scale of streaky structures. The wind-tunnel experiment for neutral stratification of Takimoto et al. (2013) demonstrated that the velocity gradient was strongly correlated with the aspect ratio of streaky structures. The relationship between the spacing λ and $\Delta U/\Delta z$ (Fig. 7c) is very clear, regardless of both stability and surface type, with the spacing λ becoming smaller with increasing $\Delta U/\Delta z$. Even plots during a typhoon followed this relationship well. LES_flat and LES_city simulations also show the same trend. The wind speed U cannot account for the spacing λ as well as vertical shear (Fig. 7b), as is apparent from the outlier for the typhoon case.

WT_cube results were very different from the real scale data, apparently due to the limitation of the dimensional approach. Below we introduce the non-dimensional parameters used to prescribe λ universally.

4.3 Scaling of the Spacing of Streaky Structures

The spacing λ and $\Delta U/\Delta z$ were normalized into λ/z_i and $(\Delta U/\Delta z)/(u_*/z_i)$ using global variables, i.e., u_* and z_i. The parameter u_*/z_i can be interpreted as a bulk gradient of the Reynolds stress for the entire boundary layer, with the dimensions of velocity gradient. As for the length scale, Lin et al. (1997) simulated a neutrally-stratified boundary layer using LES and revealed that there was a linear relationship between λ/z_i and z/z_i, which provides the maximum size of the spacing λ as a function of z_i.

Although there are two possibilities for the relevant length scales of coherent structures in the surface layer: the surface-layer height and z_i, we used z_i as a representative length scale based on the concept of a “top-down mechanism”, in which the impinging detached eddies from the outer layer onto the surface leads to the generation of small-scale eddies and upscale transfer of energy near the surface (Hunt and Morrison 2000). Detached eddies in the ABL and a neutral shear boundary layer may have different origins; however, the surface process referred to above strongly adjusted the impinging detached eddies to the local equilibrium state at the surface, with the loss of their original characteristics but the retention of the scale equal to z_i. It has been suggested that the streaky structures in the surface layer are affected by z_i-scale outer-layer eddies under weakly unstable stratification (Khanna and Brasseur 1998, Castillo et al. 2011).

As seen in Fig. 8, all of the plots for wind-tunnel experiments were converted to a single line using the non-dimensional velocity gradient (the spurious correlation between λ/z_i and $(\Delta U/\Delta z)/(u_*/z_i)$ is discussed in Appendix 3). This demonstrates that the relationship between λ/z_i and $(\Delta U/\Delta z)/(u_*/z_i)$ is universal regardless of stability, surface roughness, and the scale of motion. Plots for the DL_cloud case, shown in Figs. 7 and 8, were relatively scattered compared with the other plots, and may be because z_i in the case of the DL_cloud case was determined by the height of cloud base.

5 Discussion

Here, we provide a physical interpretation of the new scaling parameter $(\Delta U/\Delta z)/(u_*/z_i)$ for λ/z_i (Sect. 4.3, Fig. 8). In Sect. 5.1, we discuss the height variation of λ/z_i based on previous studies. Although the observation height of the Doppler lidar was constant, the relative height of the PPI scans at the zero elevation for the boundary layer varied with z_i. In addition, we cited previous studies, which provide the height variation in the spacing λ (Lin et al. 1997; details are shown in Table 3). In Sect. 5.2, the discussion is focused on the main topic, the physical interpretation of $(\Delta U/\Delta z)/(u_*/z_i)$.

5.1 Height Variation of the Spacing of Streaky Structures

The spacing λ is expected to change vertically. The increase of λ/z_i with z/z_i has been demonstrated by LES studies (Khanna and Brasseur 1998; Lin et al. 1997; Huda et al. 2016) and wind-tunnel experiments (Tomkins and Adrian 2003). In Fig. 9, previous data for neutrally stratified flows with variable height are compiled, together with the current Doppler lidar data for various stratified flows, onto the map of λ/z_i versus z/z_i. Although an increase of λ/z_i with z/z_i is apparent for individual Doppler lidar, LES, and wind-tunnel data, the different experiments (i.e., Doppler lidar, LES and wind tunnel) are still plotted apart from each other. This is because the scaling of z/z_i does not take into account the effect of the velocity gradient, as shown in Fig. 7c.

5.2 Physical Interpretation of the New Scaling

The non-dimensional parameter $(\Delta U/\Delta z)/(u_*/z_i)$was further transformed according to,

$$(k(\Delta U/\Delta z)/(u_*/z_i))^{-1} = (z/z_i)((\Delta U/\Delta z)/(u_*/kz))^{-1} = (z/z_i)\phi_m^{-1}. \qquad (8)$$

Interestingly, Eq. 8 shows that our new scaling is a product of the non-dimensional height z/z_i, i.e., the normalization used in the previous studies (Sect. 5.1, Fig. 9) and the inverse of the shear function ϕ_m^{-1}, which is a Monin-Obukov universal function. Note here that ϕ_m in the new scaling can be applied to any height, and is not limited to a constant-flux layer. Considering the relationship between λ/z_i and z/z_i (Fig. 9), the different experiments (i.e., Doppler lidar, LES, and wind tunnel) are still plotted apart from each other; in contrast, in the relationship between λ/z_i and $(z/z_i)\phi_m^{-1}$ (Fig. 8), the plots follow a single line. It was clearly shown that the regression line of the cases of the Doppler lidar (DL, DL_cloud, and DL_typhoon) were distinct from the λ profiles for the other studies (LES_flat, LES_city) in Fig. 9, while the regression line of the Doppler lidar in Fig. 8 was closer to the values of the other studies. The difference between Figs. 8 and 9 clearly indicates that the modification by ϕ_m^{-1} is effective and essential, and the physical importance of ϕ_m^{-1} as a modification factor is two-fold. The first is the modification of local shear for different atmospheric stabilities, as is the aim of the original Monin-Obukov theory. The second is the dependency of local shear on the height. Although the value of ϕ_m^{-1} might be unity within a constant flux layer, our equation aims to be applied beyond the range of this layer in which the value of ϕ_m^{-1} could be varied from unity. This is supported by the fact that an improvement from Figs. 8 to 9 is clear for neutral cases.

6 Concluding Remarks

Streaky structures in the urban surface layer were investigated based on a three-month observational dataset based on the Doppler lidar. It was demonstrated that the streaky flow patterns were more common than other flow patterns in their frequency of occurrence (e.g., cell-like and homogeneous patterns). Although the streaky structures occurred with a large horizontal wind speed and near-neutral stratification, the spacing λ varied from case to case. The most effective control parameter of the spacing λ was the velocity gradient, rather than the horizontal wind speed and stability, as shown in Fig. 7.

Finally, the discussion was expanded into the non-dimensional scaling of the spacing λ. The non-dimensional velocity gradient $(z/z_i)\phi_m^{-1}$ succeeded the scaling of λ/z_i for various categories of stability, surface roughness, and scales of motion (Fig. 8). The new scaling associated the morphology of streaky structures with the velocity gradient, as one of the most basic statistics. In addition, $(z/z_i)\phi_m^{-1}$ was a mixture of inner-layer and outer-layer scaling, although streaky structures were observed in the inner layer. This supports the validity of the top-down mechanism (Hunt and Morrison 2000).

Although the origination of the detached eddies is not clearly understood, the detached eddies are considered to follow an outer-layer scaling (Hunt and Morrison 2000; Hattori et al. 2010; Inagaki et al. 2010). Several types of coherent structures in the outer layer have been reported according to the surface roughness and heat flux. In the neutral boundary layer, the existence of very-large-scale motions has been reported (Kim and Adrian 1999), and Hutchins and Marusic (2007) observed superstructures over flat surfaces, Newsom et al. (2008) reported streaky structures having characteristics similar to superstructures over rough surfaces in terms of their aspect ratio (e.g., longitudinal over spanwise length). In a weakly unstable boundary layer, roll vortices develop regardless of the surface roughness (Khanna and Brasseur 1998; Castillo et al. 2011). However, the spacing of streaky structures in the inner layer was scaled by $(z/z_i)\phi_m^{-1}$, regardless of the scale of motion, thermal stratification, and surface roughness. This implies that the morphology of streaky structures of the inner layer is more strongly prescribed by the local shear than the morphology of the outer-layer eddy. Simultaneous observations of streaky structures at different layers are highly recommended to clarify the interaction of inner- and outer-layer flow dynamics.

Appendix 1 Investigation of Objectivity of the Visual Classification

To evaluate the objectivity of the visual classification, we calculated the statistics of the radial velocity distribution, which simply expresses the characteristics of the visual criteria in terms of (1) the convergence line, (2) the shapes of the boundary between positive and negative radial velocity, and (3) the homogeneity of the spatial pattern of radial velocity distribution. Characteristic (1) was expressed using the bulk convergence normalized by the horizontal velocity ($convergence/U$); $convergence$, which is the sum of the radial velocity in a circle with a radius of 2025 m divided by the length of the circle. Characteristic (2) was expressed as the variance of the wind direction estimated by the velocity azimuth display method for each radius from 325 to 2025 m. The variance was calculated as the magnitude of a vector that was composed of unit vectors, with the angle of wind direction for each radius. Characteristic (3) was expressed by the standard deviation of the radial velocity fluctuation in a circle with a radius of 2025 m. This fluctuation was calculated as the difference between the radial velocity and the radial component of the mean wind speed estimated by the velocity azimuth display method. Figure 10 shows scatter plots for a combination of the radial velocity statistics coloured according to a visual classification. As expected, the $convergence/U$ of the category Front was much larger than the other classes (Fig.

10a). Furthermore, the plots in Fig. 10b are clustered for each category of the visual classification. The plots of σ_θ and $\sigma_{v_r'}$ for each category agree with the criteria in the visual classification. The categories Streak, Mixed, and Fishnet had a larger $\sigma_{v_r'}$ than those of No streak and Others. In addition, the categories Streak and No streak had a smaller σ_θ than those of Mixed, Fishnet, and Others. This visual classification was supported by the objective statistics of the flow pattern. Figure 10c is the same as Fig. 10b, but only the category Streak is plotted, and the cases that were used for the analysis of the spacing λ are highlighted using different symbols. The plots used for the analysis of the spacing λ are distributed around the upper left of the figure, in which there is almost no contamination by the plots for the other categories. This demonstrated that the cases used for the analysis of the spacing λ include only typical streaky flow patterns, which were classified as the category Streak.

Appendix 2 Relationship between the Spacing of Streaky Structures Calculated by the Power Spectrum Density and Length Scales Calculated by a Two-point Correlation

The spacing λ was calculated by the power spectrum density as mentioned in Sect. 3.5. However, the past studies cited in this paper (Table 3) calculated the length scale using a two-point correlation. Therefore, we introduced a function to convert the length scale, which is estimated from the two-point correlation, to the spacing λ, based on the database of the Doppler lidar and LES_city. The spacing λ and the length scale of LES_city were calculated from the streamwise velocity fluctuation in an area of the same size as that observed by the Doppler lidar. Figure 11 shows the relationships of the non-dimensional spacing λ and the length scales from the two-point correlation for the cases of Doppler lidar and LES_city. The case of the Doppler lidar represents the ABL, which is affected by buoyancy, while that of LES_city represents the turbulent boundary layer, which is driven by only shear. The length scale $l_{minpeak}$ is the separation distance from the minimum peak of the two-point correlation. It shows a linear relationship and follows a single line regardless of the Doppler lidar or LES. Because the choice of the intercept of the regression line, i.e., zero or the best-fit value, made little difference to the estimation of the spacing λ, the regression line without the intercept was used in this study, assuming that both the spacing λ and $l_{minpeak}$ become zero simultaneously.

Appendix 3 Investigation of the Spurious Correlation in Fig. 8

Some readers may observe that the correlation between λ/z_i and $(\Delta U/\Delta z)/(u_*/z_i)$ in Fig. 8 is a spurious correlation (Pearson 1896) due to the same denominator (z_i) being present in both parameters. Hence, the validity of the scaling in Sect. 4.3 is discussed here. Figure 12 shows the same plots as shown in Fig. 8, but the colour of the plots represents the value of z_i. In the spurious correlation, the distance from the origin of the coordinate to each plot is inversely proportional to the value of z_i, whereas the equivalent distance of the plots in Fig. 12 is not proportional to the value of z_i especially in LES_flat, LES_city, and WT_cube. This supports the validity of the scaling in Sect. 4.3.

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