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ANALYSIS OF TURBULENCE STRUCTURE IN THE URBAN BOUNDARY LAYER

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INTRODUCTION

The surface layer is defined as the constant flux layer and there the effect of friction between surface and air is larger. In neutral air, the vertical size of turbulent eddy, λ_z which contains the maximum energy is proportional to the height from the ground (Kaimal and Finnigan, 1994). The mixing length, l_z, is also proportional to the height from the ground, which yields the logarithmic wind profile in the surface layer. Previous measurements in urban area show thatλ_z is proportional to the height from the ground (Högström, 1982、Roth and Oke, 1993). However the reason whyλ_z and l_z are proportional to the height from the ground, has not been discussed.

It is well known that the mixing of air in the vertical direction transports the low-speed air in the lower layer upward and the high-speed air in the upper layer downward. It yields the correlation between u' and w' and the organized structures of turbulence. Recently 'sweep' and 'ejection' have been investigated by wind tunnel and field measurements. Ropach(1981) investigated the contribution of 'sweep' and 'ejection' to the Reynolds shear stress in the boundary layer over a rough surface and a smooth surface of a wind tunnel. Rotach(1993a) and Oikawa(1995) analyzed the urban roughness sublayer turbulence using quadrant analysis and showed that the organized motion played important role in the transport of heat and momentum in the urban roughness sublayer. It is expected that there are some differences between mechanical turbulence and convective turbulence concerning the organized structures. However the varying the organized structures with atmospheric stability has not been examined. We measured atmospheric turbulence using sonic anemometers mounted at 60m in height and investigated the momentum flux, heat flux, energy spectrum of turbulence and the relation between the organized structure and atmospheric stability. Finally we represent a concept of superposed eddy model, which yields the logarithmic wind profile in the surface layer.

EXPERIMENTAL ARRANGEMENT

The measurement was conducted in an urban area of Himeji City. A tower of 75m in height was used for our study on atmospheric turbulence. A sonic anemometer system was mounted on the tower at 60 m in height from the ground. The surrounding area is flat within 2.5km southward, 4 km northward, 1.5 km eastward and 3km westward from the tower. Hills of 150 to 200 m high are in the south, east and west. Hills of 300m high are in the north. The Seto Inland Sea is 5 km in southward. In the north of the tower is a downtown with buildings of 15 to 35m in height. In the south of the tower is a commercial and residential area with buildings of 10 to 20 m in height. The measurement height is two to three times the building height and it thus corresponds to the upper part of the roughness sublayer (Rotach, 1993a) under north wind conditions and three to six times building height and it is within the inertial sublayer under south wind conditions. Two 3-D sonic anemometers (KAIJO, SAT-550) were mounted in the north and south directions for measuring the upstream oncoming wind towards the tower and we analyzed the data measured within ±22.5 °from the north or the south. The data were collected in a data recorder at a rate of 10 Hz for a 20 minute record length for each run. The measurement was conducted on August and October in 1993 and the data of August 2 at 11 a.m. to 9 p.m. and October 20 at 7 p.m. to October 21 at 11 a.m. were used for the analysis. The vertical temperature distributions were measured on October 20-21 using captive balloon at a northern residential area upwind of downtown.

RESULT OF MEASUREMENT

Atmospheric stability wind direction

The sky was fine on August 2 and the atmospheric stability was very unstable in day time (11 a.m. – 5 p.m.) and neutral in the evening (5 p.m. – 9 p.m.). On October 20, the sky was thinly overcast in the evening and cloudy at midnight and the inversion layer was observed during the night at the northern residential area. However it was almost neutral in the urban roughness layer in the downtown because Monin-Obukhov stability is $|(z-d)/L| \approx 0$ on the average. The wind direction was south on August 2 and north on October 20 – 21.

Flux and correlation

The momentum flux, temperature flux, correlation between u' and w' and correlation between w' and T' are shown in Figure 1. For unstable air in daytime, the temperature flux was about 0.2 and it decreased to 0 at sunset and it continued to be 0 through night time. However the variation of momentum flux between day and night is smaller than that of temperature flux. The atmospheric stability is estimated to be neutral at night within $3 < z/h < 6$ (h: building height) in an urban area, because it due to the mechanical turbulence caused by buildings. Usually, in rural areas measured temperature flux is downward for stable air at night.

Because the correlation between u' and T', R_{uT} was 0.4 - 0.6 for unstable air, the heat flux will be caused mainly by convective turbulence. The result is close to Kansas (country side) data (Kaimal and Finnigan, 1994). This shows that the difference in heat convection is small between urban areas and rural areas. The correlation R_{uT} decreased to 0 at night. The correlation between u' and w', R_{uw} was 0.2 - 0.3 and the difference between day and night was small. This was similar to the $R_{uw} = 0.35$ ($-1 < z/L < 1$) in Kansas data.

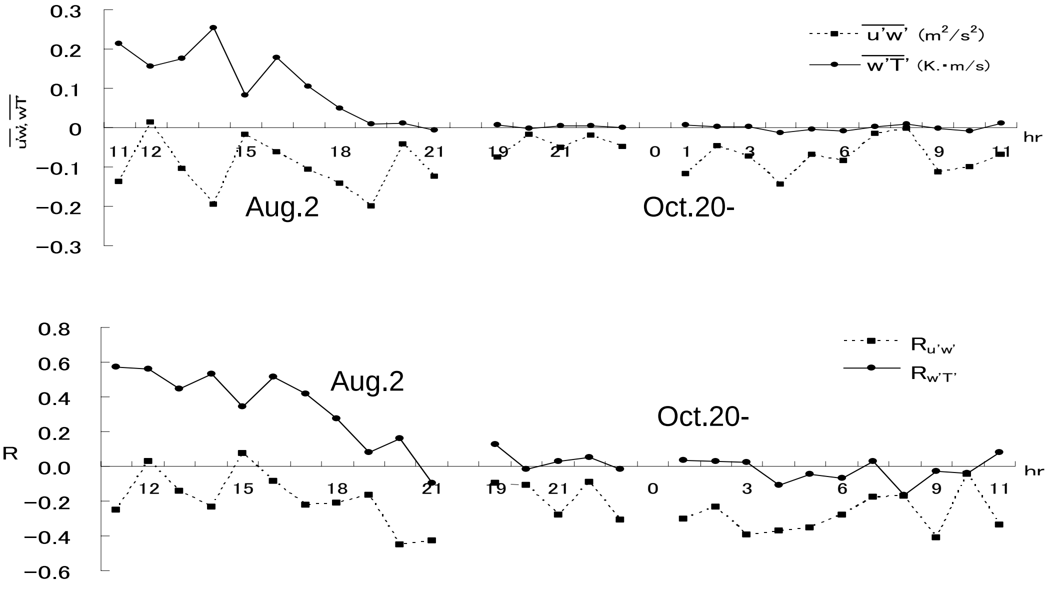


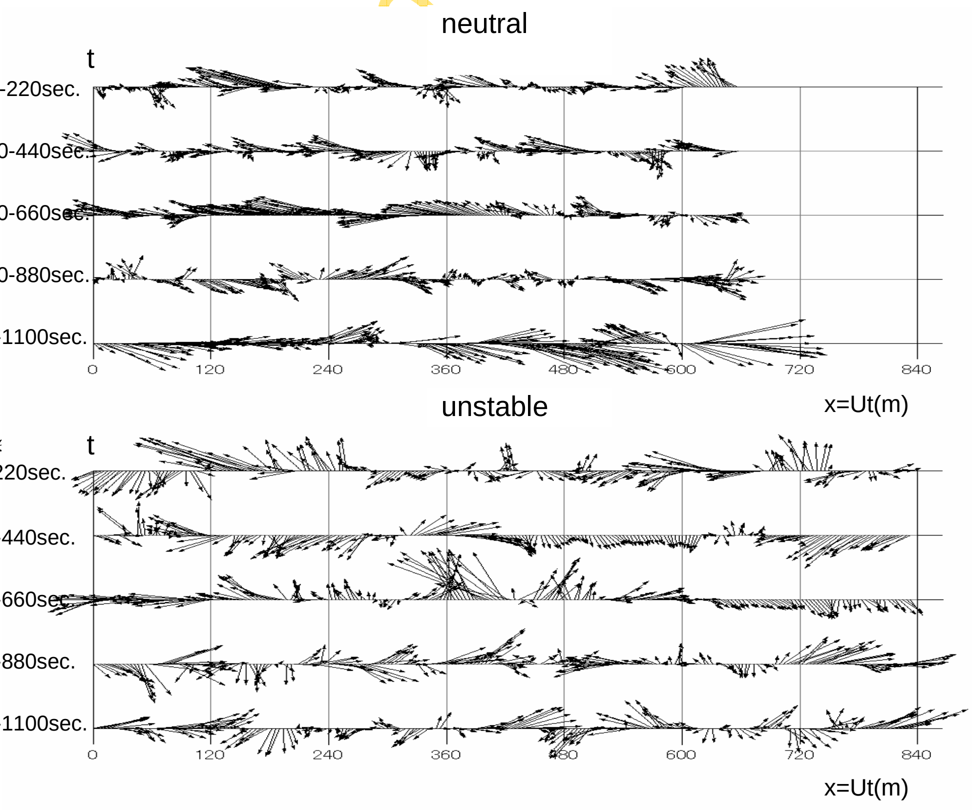
Figure 1. Momentum flux, temperature flux, correlation between u' and w' and correlation between w' and T'.

Organized structure of turbulence

Time series of vectors (u’(t), w’(t)) are shown in Figure 2 for analyzing the organized structure of turbulence. Note that the vectors in the figure represent time-mean values averaged for a period of 2 seconds. Since the wind speed is about 3 m/s the contribution to the vectors from eddies of scale less than 6 m is made zero by the averaging. By comparing the vectors for the cases of neutral and unstable air, we see that the major vector-direction is inclined to the horizontal for the neutral case, while the vertical-vector component is quite large for the unstable case. No doubt, the vectors for the neutral case represent the mechanical turbulence, while the upward vectors for the unstable case represent the convective turbulence. The same vectors are plotted in a u’- w’ hodograph plane in Figure 3. For the neutral case, the major vector direction is -20°(quadrant 4) and 160°(quadrant 2), where 0°is the positive direction of x-axis. We observed the same wind vector for slightly stable air. On the other hand for the unstable case, the major vector direction is upward, but short vectors show no dominant direction.

The eddy inclinations reflects the transport of momentum in the vertical direction $\left(-\overline{u'w'} > 0\right)$.

Matsuoka(1968) gives a parameter $\lambda = -u'/w'$ or $\lambda = -\overline{u'w'}/\overline{w'^2}$ that is related to the direction of principal axis of stress tensor in his ‘Mixing model of turbulence in the surface layer’ . The direction of the principal axis of stress tensor is the same as that of the principal axis of the eddy. Figure 3 is similar to a scatter diagram (correlation) which has often been used. The vector is a better tool to show the direction of the principal axis of eddies. The difference in eddy structure between mechanical turbulence and convective turbulence is well represented by the vector.



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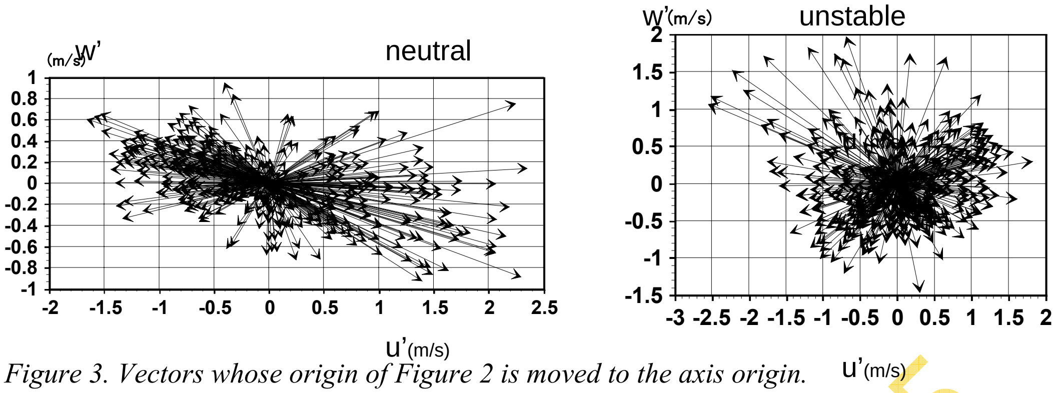

Figure 3. Vectors whose origin of Figure 2 is moved to the axis origin.

Spectral Analysis

Figure 4 shows the w-spectra and u-spectra for the unstable, neutral and slightly stable cases. Since the normalized frequency f_m at the w-spectral peak for the neutral case is approximately 0.5, the wavelength $(\lambda_m)_w$ correspond to the f_m, is approximately 2z, where z is the height of the measurement. It is almost the same as the data measured at other locations, both in urban (Högström, 1982、Roth and Oke, 1993) and in rural areas (Kaimal and Finnigan, 1994). The $(\lambda_m)_w$ is approximately 500 m for the unstable case and it is approximately $50m(=z-d;\ d=10m)$ for the slightly stable case. However even for the unstable and slightly stable cases, the spectra have a peak at $(\lambda)_w = 2z$, as shown in the plots of Figure 4.

We represent an eddy model in Figure 5 in which vertical length of an eddy is $(\lambda)_w = 2z$. Eddies are generated behind buildings and other obstacles. The eddy size increases with downwind distance like the dispersion of smoke and the kinetic energy of the eddy decreases because it is converted into heat. Therefore, we observe small eddies which have maximum energy near surface and large eddies at upper point. The eddy size is proportional to the height in the surface layer. The model will give a base of 'local equilibrium in the internal boundary layer' which has suggested by Högström et al.(1982) and 'local scaling' in the urban roughness sublayer suggested by Rotach(1993b).

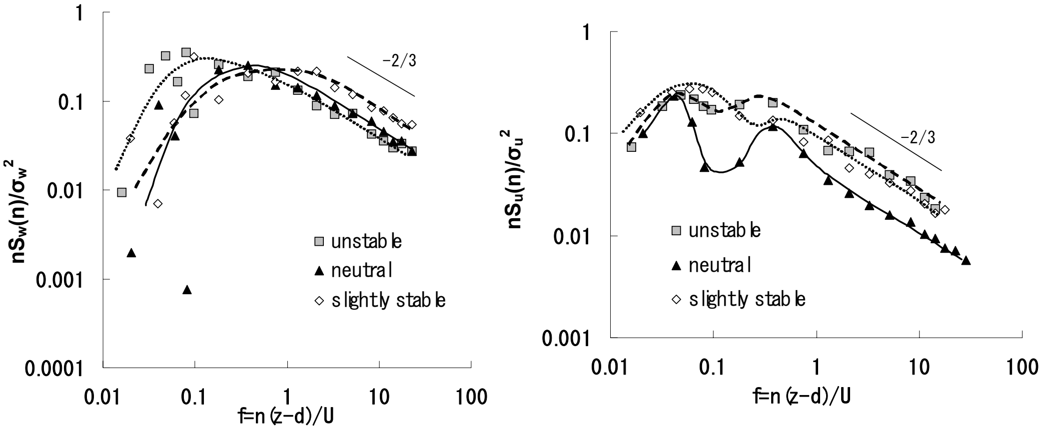

Figure 4. W-spectra and u-spectra in unstable, neutral and slightly stable air. It is calculated using FFT. The block average is used for smoothing the large scatter at high frequency.

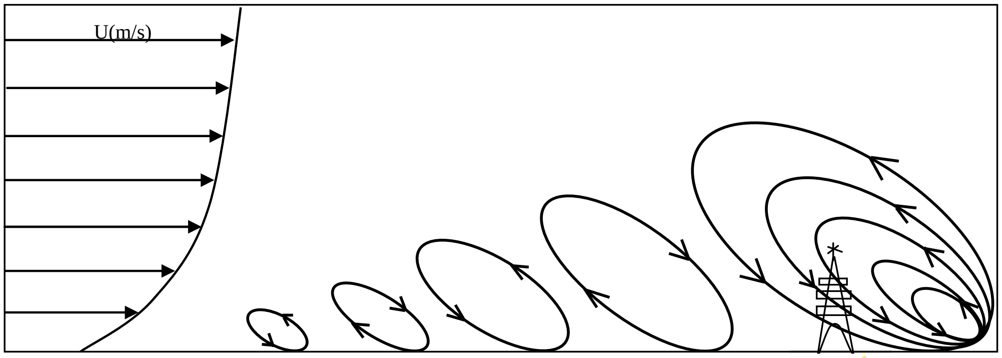

Figure 5. A superposed eddy model whose eddy size increases with downwind distance like dispersion of smoke, and the kinetic energy of the eddy decreases with the increase of eddy size because it is changed to heat energy. (neutral air)

CONCLUSION

(1) In the urban surface layer (the roughness sublayer and the inertial sublayer) of $3 < z/h < 5$, the heat flux reduce to zero and the atmospheric stability is near neutral at night.

(2) The vector representation gives the direction of principal axis of stress tensor, i.e. direction of principal axis of eddies and represents the difference in turbulence structure between mechanical turbulence and convective turbulence.

(3) We represent a superposed eddy model whose eddy size increases with downwind distance like dispersion of smoke, and the kinetic energy of the eddy decreases with the increase of eddy size because it is converted into heat. Therefore, we observe small eddies which have maximum energy near surface and large eddies at upper points. This model yields the logarithmic wind profile in the surface layer and gives a base of 'local equilibrium in the internal boundary layer'.

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