

Sensible heat flux measurement using scintillometry over urban area

Hirofumi Sugawara¹, Ken-ichi Narita², Ikusei Misaka³, Hitoshi Yokoyama⁴

¹National Defense Academy of Japan, Japan

²Nippon Institute of Technology, Japan

³Takenaka Corporation, Japan

⁴Tokyo Metropolitan Research Institute for Environmental Protection

Abstract

Large aperture scintillometer was applied for the sensible heat flux measurement over the building canopy and over the urban green. Scintillation calculation needs the effective height of the transmitted light path with high accuracy. Therefore, extreme caution should be paid for the scintillation method when it is used over the buildings of different height. As a result of validation measurement with eddy covariance method, we come to know that the canopy height should be the maximum height in the buildings, if we use the conventional morphologic method in evaluating the displacement height.

The scintillation method was applied over the largest green area in Tokyo. In summer daytime, the sensible heat flux on the green area was one thirds to half of that in the highly urbanized area.

1. Introduction

Recently, urban climate study needs surface heat flux data especially on the large area of several kilo-meters scale. For example, the large urban greens would change climate. Impact of large green area on the local airflow system should be clarified in terms of the pollution dispersion. Another example is the city-induced rain. In recent years in Tokyo, we come to have very heavy rainfall more than 50mm/hour which we had not so often experienced. The large heating on the urban surface could be a reason for the urban rain. We can see clouds lined along the cities (Inoue and Kimura, 2004), which is an evidence of the city effect on the cloud generation.

This study aims to use a large aperture scintillometer (LAS) in urban area. At first we validated LAS measurement in the highly built up area in Tokyo. Focus is on the height problem in which we have to give accurate path height to LAS calculation. The previous studies validated LAS in the flat terrain or validated in the urban area with mix convection method (Lagouarde et al., 2005). The mix convection method needs wind speed data in the flux calculation, but the free convection method does not.

The second objective of this study is the application of LAS for the green area. The Japanese imperial palace is the largest green area in Tokyo (2.3km²). However, it is strictly prohibited to get in there and we could not use sonic anemometer for the flux observation. LAS is a remote sensing sensor, so, we used LAS to measure the heat flux of the palace green.

2. Scintillometry for the heat flux measurement

Brief description of LAS measurement is noted here. LAS measures the light scintillations between the transmitter and the receiver. The scintillation is caused by the turbulence fluctuation of the air density; warmer and cooler air mass crossing the light. We

get the structure constant for temperature C_T^2 from the scintillation and apply it to the Monin-Obukhov similarity theory.

$$\frac{(z-d)^{2/3} C_T^2}{T_*^2} = f\left(\frac{z-d}{L}\right) \quad (1)$$

where z is the height of the path, d is the canopy displacement height, L is the Monin-Obukhov length scale, T_* is the friction velocity, and f is the universal function for the similarity theory. For the unstable layer, especially in the thermally-driven free convection ($z/L \rightarrow -\infty$), the similarity equation gets into simple.

$$H_{snt} = \rho c_p b (z-d) (g/T_a)^{1/2} (C_T^2)^{3/4} \quad (2)$$

We can get sensible heat flux from the C_T^2 , z and d . This method is called free convection method. ρc_p is the volumetric heat capacity of air, g is the gravity constant, T_a is mean air temperature, b is the constant. The merit of LAS is its wide area. The maximum distance between the transmitter and the receiver can be several kilo-meters. On the other hand, the sonic anemometer at the 30m high tower would measure typically 0.003km^2 area. However LAS measurement is based on the Monin-Obukhov similarity theory. We are not sure it always holds in the urban area. And also, LAS requires accurate height data of the light path.

3. Site description

The measurement had been continued for one month in summer 2007. The validation measurement, in which we compare LAS measured heat flux to that by reference eddy covariance method was taken in the highly-built-up area in Tokyo. The transmitter and receiver of LAS was set-up 800m apart. It was less than the kilo-meter scale, but LAS position was determined so as to match the flux source area between LAS and eddy covariance. The sonic anemometer (Kaijo SAT-550) was set up at the 110 m (50 m) high above the ground level (mean roof level). In this period, we also took LAS measurement simultaneously over the large green area in Japanese imperial palace. In Fig. 1, two paths of scintillometer are shown. The path above green area is 2.2 km long.

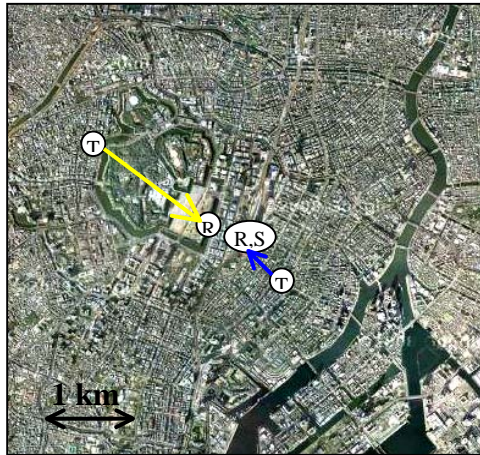


Fig. 1: Observation area. T: LAS transmitter, R: receiver, S: sonic anemometer. Arrows indicate the light path of LAS.

4. Height problem in scintillometry measurement

The LAS equation (eq.2) includes the canopy displacement height d . The buildings make the virtual boundary between the atmosphere and ground. Height of the boundary is the displacement height. For the homogeneous canopy, d has been studied theoretically (Jackson, 1981) and experimentally in the wind tunnel (Macdonald, 1998). d increases as the canopy gets denser. The morphologic method expressed d as a function of canopy geometrical index. If we use the morphologic method, ratio of d to the canopy height d/z_{canopy} is 0.61 for this site (frontal area index 0.13, plane area ratio 0.36).

However, the real urban canopy is not homogeneous. Size of each building area not uniform. So we do not know the morphologic method for the homogeneous height canopy folds true in the heterogeneous canopy. There is a comprehensive work including the review of morphologic method by Grimmond and Oke (1999). They did not find success of morphologic method in the real urban area. The heterogeneity could be doubttable.

Here, we assumed that the conventional morphologic method holds true for the heterogeneous canopy. Instead, we inspected the z_{canopy} . In other word, we evaluated an effective height of the heterogeneous canopy for the use of morphologic method. If we accept maximum height of the buildings, z_{canopy} is 39.2m, and for the average height 22.0m. Two choices of z_{canopy} would be tested in the next section.

5. Result

Diurnal variation of heat flux was shown for four days. Solid line is the flux by eddy covariance. Red cross is the LAS result using average building height. White circle indicates LAS with maximum building height. LAS data is plotted when the atmosphere is thermally unstable where vertical gradient of potential temperature is less than -0.04 K/m. White circle agrees well with the line, but red cross overestimates. Thus, the maximum building height is more adequate as the effective canopy height than the average height is.

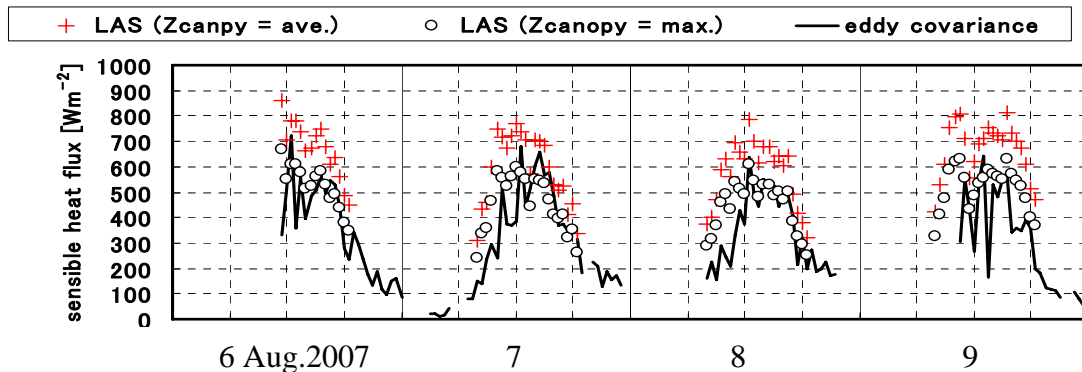


Fig. 2: Comparison of LAS measured heat flux (marks) to that by the eddy covariance method (line). LAS heat flux was calculated by two types of canopy height. Sequential diurnal variation of four fine days are shown.

We could give some interpretation for the two kinds of height. In the homogeneous canopy, the maximum height equals to the average one. So we do not find any discrepancy when we use existing morphologic method in the homogeneous canopy. However, in the heterogeneous canopy, roof size and building height are all different between buildings. So, the simple average which does not consider the roof area difference should have less physical meanings. On the other hand, dynamical and/or thermal influence of the buildings on the atmosphere could spread over the tallest buildings above the building canopy. Therefore, for the atmospheric layer, the maximum height of the building could be one kind of boundary.

6. Application of LAS to the large green area

Sensible heat flux in green area of the Japanese imperial palace was measured by LAS and compared to that in the highly urbanized area (Fig.3). Filled circle is the highly urbanized area and open one is the green area. The thin line, net radiation on urbanized area and thick line, anthropogenic heat in the urbanized area are also presented. The anthropogenic heat was evaluated from the statistics of energy consumption. The sensible heat flux exceeded the net radiation because of the anthropogenic heat. The green area has sensible heat flux of half or one thirds of urbanized area. There is average 400 Wm^{-2} difference between the urban and green in daytime. Among 400 Wm^{-2} , 200 Wm^{-2} would be due to the urban anthropogenic heat. Another 200 Wm^{-2} should be effect of the evapotranspiration by the vegetation.

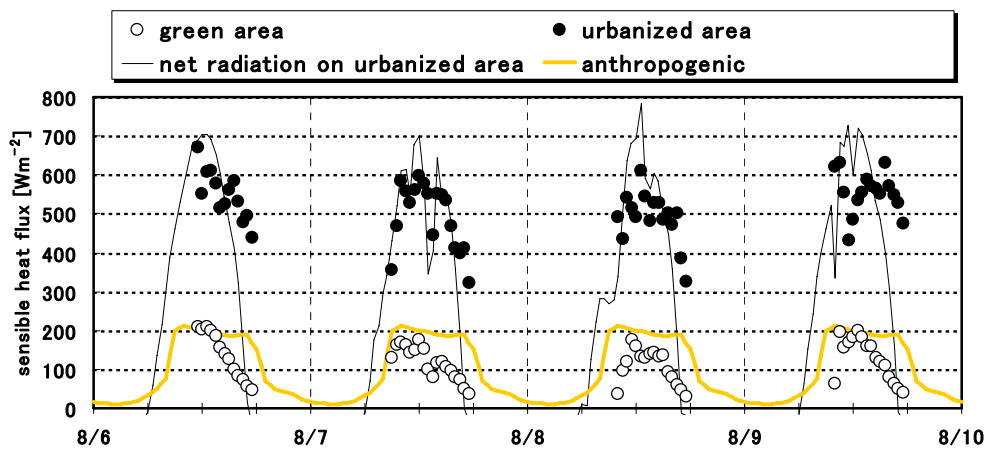


Fig. 3: Sensible heat flux in the large green area and urban area.

7. Conclusions

Large aperture scintillometer was applied for the sensible heat flux measurement over the urban canopy and large urban green. Scintillation method needs the effective height of the transmitted light path in the calculation. We have to evaluate canopy displacement height in the heterogeneous urban canopy. Validation measurement with eddy covariance method, resulted that the canopy height should be the maximum height in the buildings if we use the conventional morphologic method to get the canopy displacement height.

The scintillation method was applied over the largest green area in Tokyo. In summer daytime, the sensible heat flux on the green area was one thirds to half of that in the highly urbanized area. Half of the heat flux difference between the green and city would be due to the anthropogenic heat. The other half would be the evapotranspiration effect.

Acknowledgement

This work is financially supported by the Japanese ministry of environment and Tokyo metropolitan government. The authors would express thank to the Chuou award office, Sumitomo Shouji Corp., Tokyo International Forum Corp., and Tobishima Corp, who facilitated our measurement.

References

- Inoue, T. and F. Kimura, 2004: Urban effects on low-level clouds around the Tokyo metropolitan area on clear summer days, *Geophys. Res. Lett.* 31, L05103, doi:101029.
- Jackson, P. S., 1981: On the displacement height in the logarithmic velocity profile, *J. Fluid Mech.* 111, 15-25.
- Grimmond C. S. B. and T. R. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of surface form, *J. Appl. Meteorol.*; 38, 1262-1292.
- Lagouarde, J.-P., M. Irvine, J.-M. Bonnefonde, C. S. B. Grimmond, N. Long, T. R. Oke, J. A. Salmond, B. Offerle, 2005: Monitoring the sensible heat flux over urban areas using large aperture scintillometry: case study of Marseille city during the ESCOMPTE Experiment. *Bound.-Layer Meteorol* 118, 449-476.
- Macdonald, R.W., Griffiths, R.F., Hall, D.J., 1998: An improved method for the estimation of surface roughness of obstacle arrays, *Atmos. Environ.* 32; 1857-1964.

Authors' address:

Dr. Hirofumi Sugawara (hiros@nda.ac.jp)
National Defense Academy of Japan
Hashirimizu Yokosuka, Kanagawa, Japan

Prof. Dr. Ken-ichi Narita (narta@nit.ac.jp)
Nippon Institute of Technology, Japan
Miyashiro Minami-saitama, Saitama, Japan

Dr. Ikusei Misaka (misaka.ikusei@takenaka.co.jp)
Takenaka Corporation, Japan
Ootsuka Inzai, Chiba, Japan

Dr. Hitoshi Yokoyama(yokoyama-h@tokyokankyo.jp)
Tokyo Metropolitan Research Institute for Environmental Protection
Shinsuna Koutou, Tokyo, Japan