Journal of Heat Island Institute International Vol. 9-2 (2014)

Academic Article

How much does urban green cool town?

Hirofumi Sugawara[*1], Shogo Shimizu[*2], Shinsuke Hagiwara[*3], Ken-ichi Narita[*4], Takehiko Mikami[*5]

*1 National Defense Academy of Japan

*2 Tokyo Metropolitan Univ. (present affrication: Hokkaido Government)

*3 National Museum of Nature Study

*4 Nippon Institute of Technology
*5Teikyo Univ.

Corresponding author: Hirofumi Sugawara, hiros@nda.ac.jp

ABSTRACT

The cooling phenomenon brought by a large urban green park in Tokyo to its surrounding town area was evaluated. Micrometeorological measurements conducted during summer nights revealed the heat balance for the park's forest canopy. Highly reliable measurement runs, in which independent evaluations agreed within 20%, showed that the cooling amount was 60 Wm^{-2}, which is equal to the nocturnal heating in the surrounding town area.

Key Words: Green cool island, Urban park, Advection

1. Introduction

Urban greening is an effective mitigation factor for urban heat islands. Many previous studies $^{(1),\ (2)}$ clearly showed that an urban green park is cooler than the surrounding town in summer, i.e., a cool green island. However, none of these studies, including ours, adequately evaluated the cooling amount generated by a green park. These studies were based on the measured air temperature distribution, although the temperature distribution is not enough to evaluate the cooling amount because it is a result of heat exchange between the green park and the surrounding town. For example, picking up the cold air advection from the green park to the town, the advected air mass is heated by the warmer materials on roads. Normal thermometers cannot capture this transition because the time scale of turbulent mixing is close to the time response of the thermometer, which is a few minutes for commonly used sensors. Here, the time scale of mixing can be estimated as L^2/K, where L is the length scale (here, the building height in surrounding areas, 10 m), and K is the turbulent diffusion coefficient (on the order of 1 m^{2}s^{-1}). Therefore, what we measured in previous studies was the already heated air above roads. The balance between heating by roads and advective cooling (cooling amount) determines the air temperature distribution. The cooling amount produced by green parks cannot be evaluated using the thermally balanced temperature distribution.

The distribution of surface air temperature is a basic piece of information in urban climate study, showing the locations of warmer or cooler air masses. In contrast, the cooling amount, which should be expressed as heat flux in Wm^{-2}, is a more important quantity that needs to be determined in order to evaluate the worth of green parks in cities.

In this study, we evaluated the cooling amount produced by a large park in Tokyo, focusing on summer nights. We estimated the heat balance of the forest canopy in an urban park, which is also a recent topic in forest meteorology (3). The measurement accuracy of advective heat flux is a big problem in rural forests because the horizontal temperature gradient in forests is small. However, in our case of an urban forest, the large temperature gradient between park and town produced a large advective heat flux. We also checked for closure of the heat balance in the forest canopy in order to present results with high accuracy.

2. Measurements

The study site was the urban park of the National Museum of Nature Study, located in Shirogane, Tokyo (Fig. 1). The surrounding town is a highly built-up commercial area. The park has an area of 0.2 km^2, and is covered by a deciduous forest whose mean height is 14 m.

Measurements were taken during the summer of 2009. The sensor setup is shown in Fig. 2. We installed instruments for turbulence and radiation measurements at the top of a mast (20 m from the ground, 6 m from the forest crown). The mast was located at the center of the park. A sonic anemometer (Kaijo SAT-540) and H_2O/CO_2 analyzer (Licor LI-7500) measured the vertical turbulent heat flux with the eddy covariance method, where the correction for air density and axis rotation for the terrain following flow were taken. The radiometer (Kipp & Zonen CNR-1) measured upward and downward radiation in the shortwave and longwave ranges.

We captured outflow from the park by installing two sonic anemometers (GILL windsonic) and two thermometers (T&D RTR-52A) at the north and south boundaries of the park. We also installed thermometers at 24 points inside the park to acquire the temperature distribution. The thermometers were equipped with a radiation shield, and were ventilated naturally. The measurement height was 2.5 m, and the time interval was one minute.

In the summer of 2010, we took temperature profile measurements at three points (the center mast, northern, and southern edges) in the park. Thermometers of the same type as those used in 2009 were hung at eight levels, from 2 m above the ground to the top of the canopy (16 m).

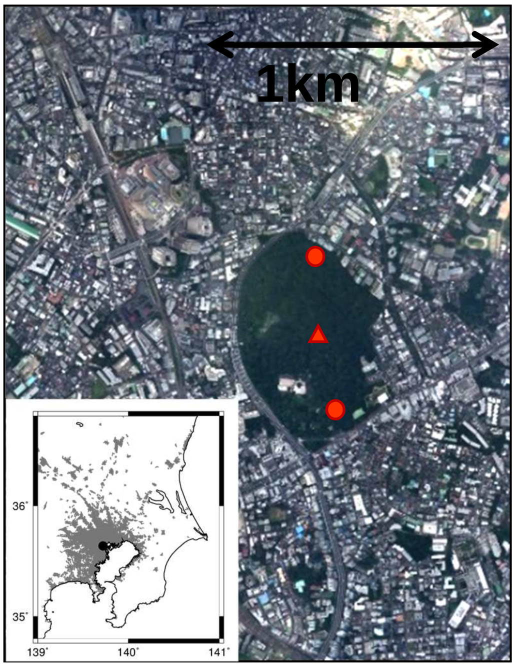

Figure 1. Study area. Solid circle in inset map indicates the position of the park. Gray hatched area is the Densely

Inhabited District. Triangle indicates mast location; circles indicate locations of anemometer and temperature profile measurements.

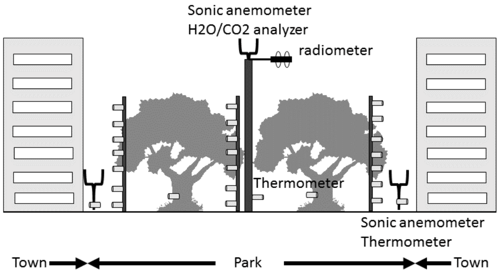

Figure 2. Schematic illustration of instrument setup.

3. Analytical procedure

We evaluated the heat balance of the forest canopy layer in the park. The analysis volume covers the forest canopy, with the soil surface at the forest floor as the lower boundary, and the tree crown as the upper boundary. The heat balance of the volume is shown in Fig. 3 and written as

$$Q_H + Q_E + R_{net} + Q_g + Q_{adv} + Q_a + Q_w = 0 , \qquad (1)$$

where each term is positive, as heat flows from the inside to the outside of the analysis volume. Q_H and Q_E are the sensible and latent heat fluxes, respectively, at the top of the canopy, and are acquired from the eddy covariance measurements at the tower. R_{net} is the net radiative flux, also measured at the top of the tower. Q_a, Q_w, and Q_g represent heat storage by the canopy air mass, vegetation body (trunks, stems, and leaves), and ground soil, respectively. These are evaluated as

$$Q_a = c_a \rho_a (1 - R_w) h_t \frac{\delta T_a}{\delta t} , \qquad (2)$$

$$Q_w = c_t \rho_t R_t h_t \frac{\delta T_t}{\delta t} + c_s \rho_s V_s \frac{\delta T_s}{\delta t} , \qquad (3)$$

and

$$Q_g = c_g \rho_g d \frac{\delta T_g}{\delta t} . \qquad (4)$$

Here, c is the specific heat, ρ is the density, and the subscripts a, t, s, and g indicate air mass, trunk, stem (including leaves), and ground soil, respectively. R_w is the area ratio of the tree trunks (6% based on the every-tree inventory), and h_t is the mean height of the trees (14 m), which is equal to the height of the analysis volume. V_s is the volumetric ratio of the stems and leaves (here assumed to be 15% based on the value for a typical Japanese forest). The variable d is the length scale of underground temperature change, which can be evaluated as

$$d \approx \left(\frac{\lambda_g}{c_g \rho_g} t \right)^{1/2} , \qquad (5)$$

where λ_g is the heat conduction coefficient of soils, and t is the time scale. The value of d was 3 cm because the time scale of flux evaluation in this study was 30 min. For T_a, T_w, and T_g, we used air temperature measured 2.5 m above the forest floor because the forest was so dense that radiative equilibrium, i.e., isothermal conditions could be assumed inside the canopy. The other constants are listed in Table 1.

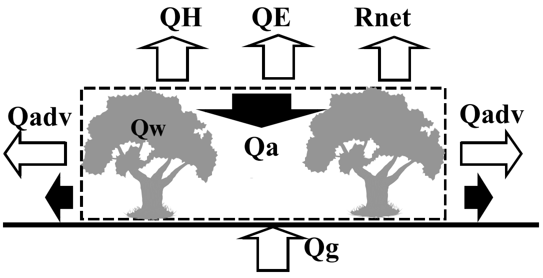

Figure 3. Definition of heat flux components in the forest canopy. The rectangle indicates the volume analyzed. Black and white arrows indicate airflow in the divergent park breeze situation and heat flux, respectively.

Q_{adv} is the advective heat flux at the park boundary, which indicates the cooling amount generated by the park. We evaluated Q_{adv} using two methods. One method used the residual of eq. (1). We call this the indirect evaluation, and denote it Q_{adv_in}. The other method is named the direct evaluation, Q_{adv_di}, expressed as

$$Q_{adv\_di} = c_a \rho_a h_a L \left(T_{park} - T_{town} \right) U / S \quad , \qquad (6)$$

where h_a is the depth of cold air flow at the park boundary, L is the circumference of the park, and S is the area of the park. This expression of advection was applied for the divergent park breeze case, whose flow system is shown in Fig. 3. T_{park} and T_{town} are the representative air temperatures of the park and surrounding town, respectively. We used the average of 24 points measured in the park for T_{park}, where the range of spatial variation is about 1 K.

T_{town} was measured at the residential district 2 km away from the park, which was far enough from the reach of park breeze. Using the temperature measured at only one point for T_{town} suffers from the influence of the spatial heterogeneity of urban air temperature, and obtaining the spatial average is quite difficult. Intensive measurements using a car revealed that the spatial variation of air temperature in downtown Tokyo is 0.3 K at night (4). The temperature difference (T_{town} - T_{park}) in the case shown in the section 5 (September 10-11, 2009) is 3 K, so the spatial variation might cause 10% difference in the Q_{adv_di} evaluation.

U is the wind speed component perpendicular to the park boundary, and was an average of measurements at the south and north edges of the park in the analysis. The spatial variation of U is also problematic. Wind measurements at eight points in this park in 2014 revealed a spatial variation of 0.1 ms^{-1} for U when the divergent park breeze occurs, which might cause a 50–100% difference in Q_{adv_di} evaluation.

Only the horizontal wind speed is included explicitly in this evaluation, but vertical advective flow at the top of the canopy is implicitly included in eq. (6). The reason is shown here by deriving eq. (6). When the divergent flow occurs at the park lateral edges, the downward flow at the canopy top compensates for the mass budget in the volume analyzed. The air mass budget can be written as

$$WS = ULh_a \quad . \qquad (7)$$

The left and right hand sides of eq. (7) indicates the heat mass flux at the top of canopy and flux at the lateral boundary, respectively. W is the vertical wind speed at the top of canopy. The heat flux at the top and lateral surface of the volume analyzed are

$$Q_T = c_a \rho_a S T_{urban} W \quad \text{and} \qquad (8)$$

$$Q_L = c_a \rho_a h_a L T_{park} U \quad \text{, respectively.} \qquad (9)$$

The advection flux in the volume analyzed is the residual of out-flux at the lateral surface (Q_L) and influx at the top (Q_T),

$$\begin{aligned} Q_{adv\_di} &= Q_L - Q_T \\ &= c_a \rho_a h_a L T_{park} U - c_a \rho_a S T_{urban} W \ . \end{aligned} \qquad (10)$$

Substituting eq. (7) into eq. (10) derives eq. (6).

Analysis was conducted for each run of 30 min. Independent evaluations of Q_{adv} (indirect and direct) were compared, and runs with good agreement were selected for further analysis.

Table 1. List of constants. Values for wet clay were used for $c_g\rho_g$ and λ_g.

$c_t\rho_t$	7.2×10^3 $\mathrm{Jm^{-3}K^{-1}}$
$c_g\rho_g$	6.0×10^3 $\mathrm{Jm^{-3}K^{-1}}$
$c_s\rho_s$	7.2×10^3 $\mathrm{Jm^{-3}K^{-1}}$
λ_g	2.0 $\mathrm{Wm^{-1}K^{-1}}$

4. Depth of cold air outflow

For the analysis, we need the depth of cold outflow h_a in eq. (6), which was evaluated as follows. The vertical profile of air temperature in the park was measured in 2010. Figure 4 shows the time variations. The correlation coefficient shown was calculated between the air temperature at the top (16 m) and at each level over a two hour period. Figure 4 indicates accumulated cold air at the bottom after 0 JST, and the decreased correlation coefficient. This means that the air mass at the bottom has different thermal characteristics from that at the top, and the depth of the cold air mass can be determined from the decrease of the correlation coefficient. Figure 5 shows profiles of the correlation coefficients. After 0 JST, the correlation coefficient decreased below 14 m height. We determined the depth of cold air at 15 m, considering the uncertainty due to the 2 m interval measurements. The depth of cold outflow evaluated here is very close to that at other points in the park and also close to the mean tree height. Measurements in other parks in Tokyo also showed that the depth of park outflow is close to the tree height (5). Therefore the value of h_a is assumed to be constant (15 m) in the following analysis.

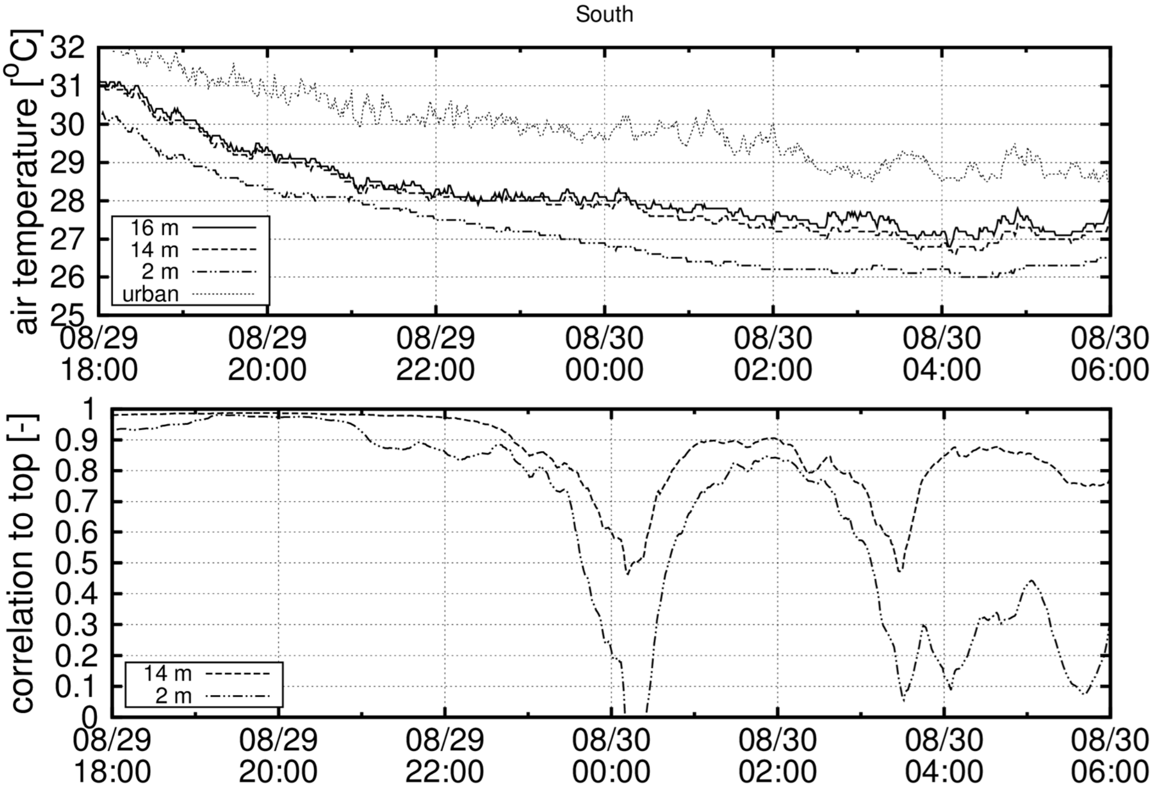

Figure 4. Time variation of air temperature and its correlation coefficient for August 29–30, 2010. The correlation coefficient is

calculated using air temperatures at 16 m and at each height over a two hour period.

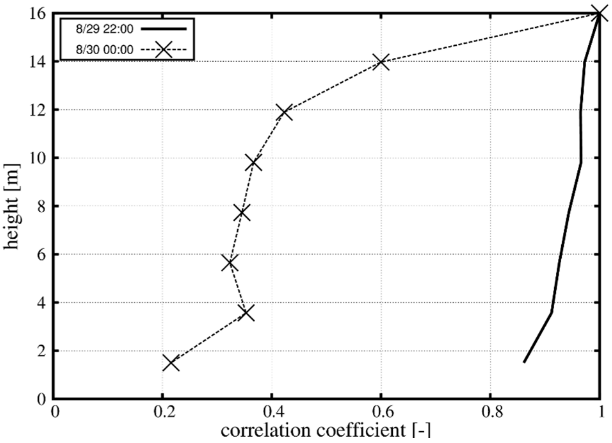

Figure 5. Vertical profile of correlation coefficients for August 29–30, 2010.

5. Heat balance analysis

We select one night time series, and discuss the wind flow system and heat flux in detail. Figure 6 shows the time variation of temperature, wind, and heat flux on September 10–11, 2009. The weather was cloudy, but no rain event was detected. After 23 JST, the wind became calm above the canopy, and divergent wind appeared at the surface. At the same time, air temperature at the northern and southern park boundaries dropped rapidly, indicating cold air outflow. The divergent wind system was probably caused by the gravity flow of cold air from the park to the surrounding town. This divergent wind was also found at other parks in previous studies (1), (6), and is often called the divergent park breeze. In this situation, the independently evaluated Q_{adv} values were in good agreement, probably because of the stable wind flow system. R_{net} was close to Q_{adv}, indicating that the green park generated cold air by radiative cooling, and the outflow brought most of the generated cold engergy to the town.

The cooling amount in this situation is 60 Wm^{-2}. This cooling amount is nearly equal to the heating amount in the urban area at night (55 ± 22 Wm^{-2}) measured above the building canopy in downtown Tokyo (7), which means that the green park quantitatively cancels out urban heating by features such as road surfaces and cars.

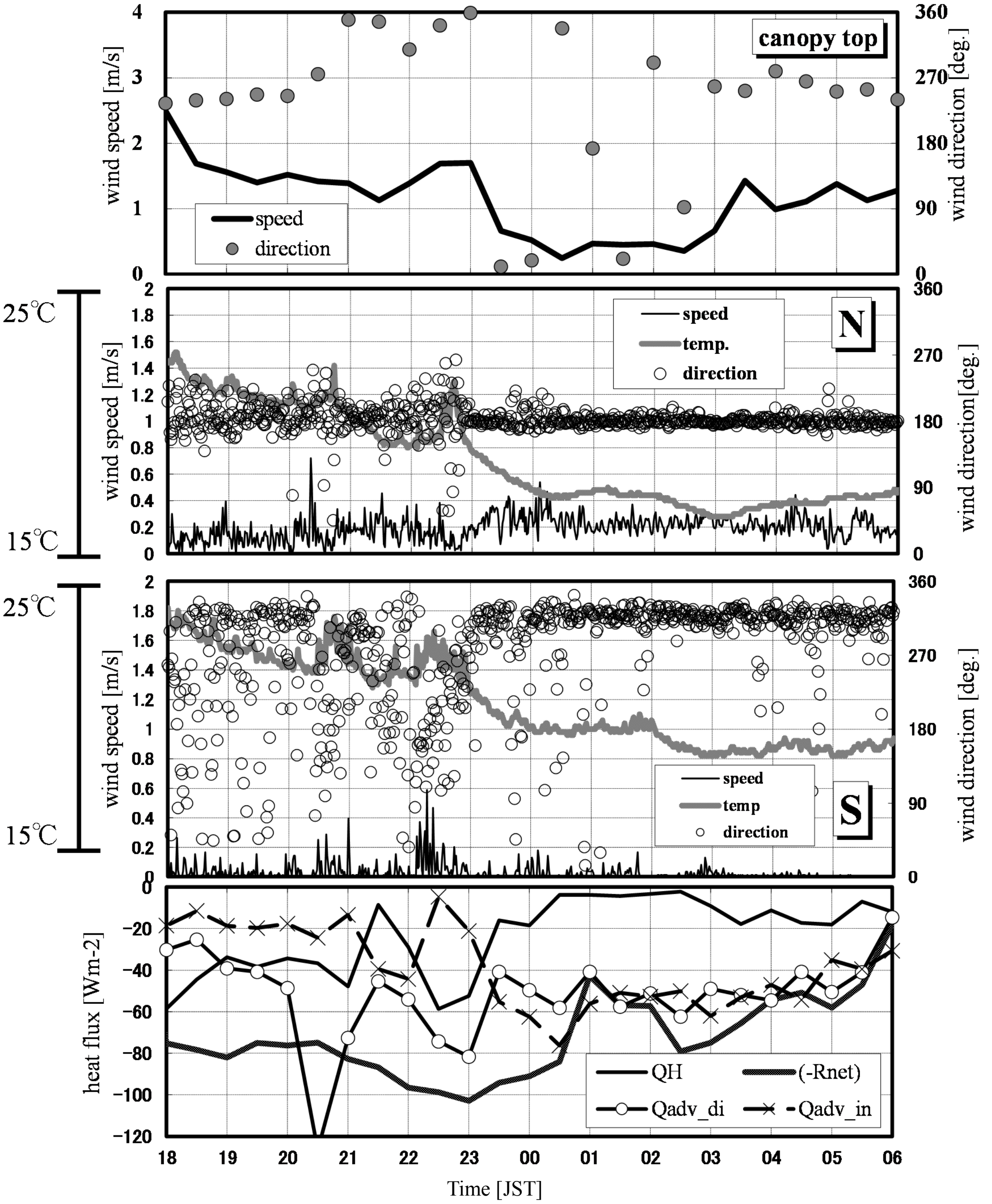

Figure 6. Time variation of air temperature and wind speed at the northern and southern park boundaries (upper three panels), and heat flux (lowest panel) for September 10–11, 2009. Q_H: sensible heat flux, R_{net}: net radiation flux, Q_{adv_in} and Q_{adv_di}: advective heat flux by indirect and direct evaluation, respectively.

6. Reference

[1] K. Narita, T. Mikami, H. Sugawara, T. Honjo, K. Kimura and N. Kuwata, Cool-island and Cold Air-seeping Phenomena in an urban park, Shinjyuku Gyoen, Tokyo, Geographical Rev. of Japan 77 (2004), pp.403-420

[2] H. Upmanis, I. Eliasson, S. Lindqvist, The influence of green areas on nocturnal temperatures in a high latitude city (Goteborg, Seden). Int. J. Climatol. 18 (1998), pp.681-700

[3] M. Aubinet, Feigenwinter, C., Heinesch, B., Bernhofer, C., Canepa, E., Lindroth, A., Montagnani, L., Rebmann, C., Sedlak, P. & Van Gorsel E. Direct advection measurements do not help to solve the night-time CO2 closure problem: Evidence from three different forests. Agric. and Forest Meteorol. 150 (2010), pp.655-664

[4] T. Takano, K. Narita, T. Mikami, H. Sugawara and T. Honjo. Spatial average and variation of radiation and temperature within a street canyon: Case study in the city area around Shinjyuku Gyoen park. Pap. Env. Information Sci. 17 (2003), pp.47-52

[5] H. Sugawara, K. Narita, T. Uchika, T. Takano and T. Mikami. Cold outflow in the urban park., Proc. Spring Meeting Japanese Meteorological Society (2004)

[6] I. Eliasson, and H. Upmains, *Nocturnal airflow from urban parks-implications for city ventilation.* Theor. Appl. Climatol. 66 (2000), pp.95-107

[7] H. Sugawara, S. Shimizu, K. Narita, T. Mikami and S. Hagiwara. Sensible heat flux in the Institute for Nature Study -comparison with the surrounding building area-. Miscellaneous Reports of the Institute for Nature Study 44 (2013), pp.9-13

(Received Dec. 19, 2014, Accepted Dec. 27, 2014)