Effects of Urban Geometry on Urban Heat Islands in Tokyo
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Abstract

Using the satellite thermal image data of ASTER and air temperature data measured through the high density observation system (METROS), we investigated the effects of urban geometry on the Urban Heat Islands (UHIs) in Tokyo. The land surface temperature in the center of city is lower in the morning and higher in the evening than that of the surrounding area, and highly correlated with the coverage rate of mid-to-high-rise buildings (CRMB). The same relationship can be also found between the atmospheric temperatures and the CRMB. The results of this study indicate that the effects of urban geometry, both with the shading effect in daytime and with the reducing radiation cooling and increasing thermal storage effect at night, are the important factors in the UHIs of Tokyo.

Key words: Heat Islands, Surface temperature, Air temperature, Urban geometry, Tokyo

1. INTRODUCTION

The urban heat island phenomenon is generally defined as the warmer air temperatures compared with those over the rural surroundings. In the ward area of Tokyo, most of the areas are urbanized and equally covered with artificial materials except in some green parks. But the distribution of air temperature is not homogeneous and includes some regionalities. In this case, the urban geometry, which refers to the dimensions and spacing of buildings within a city, can be considered as one of the most influential factors on the thermal environment.

We conducted this study as part of TMG’s action program to mitigate UHIs of Tokyo. And our objective is to clarify the effects of the urban geometry on the UHIs of Tokyo.

2. STUDY AREA

Tokyo Metropolis is located around the center of Japanese main island Honshu (Fig. 1) and can be divided into two areas (except for several islands in Pacific Ocean); rural-to-suburban Tama District and highly-urbanized Ward Area. The ward area has 622 square kilometers and faces Tokyo Bay to the southeast. The western half of this area is hilly terrain below 50 meter above sea level and the eastern half is plain lowland. The most urbanized area, surrounded by several designated new urban zones, is shown in Fig. 2. Large green parks mainly exist in the western area and large-scale housing developments are located in the northern area.

3. DATA AND METHOD

3.1. Urban Geometry Data

The ward area of Tokyo consists of 3,135 small districts named cho-chou-moku (which is the unit of local community and the postal district. Hereinafter abbreviate as CCM). The CCMs vary in size and the mean area of all CCMs can be calculated to about 0.2 km².

The Tokyo Metropolitan Government (TMG) has provided many kind of land-use statistics based on the CCM. We used the coverage ratio of mid-to-high-rise building (CRMB) as the urban geometry parameter of Tokyo. The CRMB, shown in Fig. 3, is given as the areal ratio of buildings with more than 3 stories to whole buildings in each CCM (TMG, 2003).
3.2. Land Surface Temperature  
For investigating the influence of CRMB on surface temperature, the ASTER surface temperature products (2B03) with the spatial resolution of 90m was utilized. These images are already completed the geometric and atmospheric correction and provided by the Earth Remote Sensing Data Analysis Center (ERSDAC).

The following four image data were selected for examining the seasonal and diurnal differences between the warm and cold seasons, though their periods are not completely consistent because of the restriction of data.  
**Nighttime:** 13th Aug. 2004, 21.47 JST  
**Daytime:** 5th Sep. 2003, 10.38 JST  
28th Feb. 2004, 10.47 JST

These images were processed to pseudo color images and trimmed away outside of the boundary of the ward area of Tokyo. And for analyzing the statistical relationship between the surface temperature and CRMB, spatial mean surface temperature were calculated with respect to each CCM area.

3.3. Atmospheric Temperature  
For the atmospheric elements, we used the meteorological data observed by METROS which is the automated meteorological observation system established by the TMG in 2002 (Fig. 4). This system consists of two subsystems, METROS20 and METROS100. The former system can measure various meteorological parameters with high precision while the latter can observe air temperature and humidity with highly spatial resolution in Tokyo.

Wind speed and rainfall data of METROS20 were used for selecting typical days with calm night and no-rain. And for analyzing the relation of urban geometry to the air temperature, the data obtained by METRO100 were used.

1) **Mean maximum and minimum temperatures in summer**  
In Tokyo, the end of the Baiu (rainy season in Japan) is usually around on 20th of July. Therefore we considered the period from 20th of July to the end of September as that representing the summer of Tokyo. Mean maximum and minimum temperatures in the summers in 2003 and 2004 were calculated. The summers in 2003 and 2004 was characterized by cooler condition than normal and very hotter one, respectively.

2) **Diurnal change of air temperature**  
For obtaining the typical mean diurnal change of air temperature in each station of METROS100, 6 days were selected in the case of calm-night and no rainfall by using the wind and rainfall data observed with METROS20 from 1st of July to 30th of September in 2004. The 6-day mean values in the station are calculated in each time. Additionally, the mean diurnal change of air temperature was computed as the spatial mean values using all of the stations in METROS100.

4. RESULTS AND DISCUSSION  
4.1 Characteristics of land surface temperature distribution  
1) **Nighttime**  
The land surface temperature images at the nighttime (21.47 JST) are shown as N1 for warm period and N2 for cold period in Fig. 5. Both images have a similar tendency that the temperatures increase in the center of city compared to their surroundings. More precisely, high temperatures significantly expand from Urban Center to Designated Urban zones and along main roads where large amount of waste heat can be exhausted by urban activities. Around the large housing developments like
Takashimadaira, Hikarigaoka and Kirigaoka, the surface temperatures are also remarkably higher than their surroundings. A comparison between N1 and N2 indicates that the regional difference of surface temperature in N2 is more significant than that in N1. As for N1, the warmer areas seem to be corresponding to the areas where the daily maximum air temperatures are relatively high. Therefore it is thought to be caused by the effects of the heat stored in the ground during the daytime. In contrast, for the cold period, N2, because of weak solar irradiance and inactive vertical motion, the effects of waste heat are stronger than the heat stored during the daytime. Therefore the typical surface UHI pattern will be formed.

And other remark of seasonal difference occurs between the temperatures of water areas and of land areas. In winter, the water areas are quite hotter than the land areas, but in summer the temperatures in both areas are almost same. It can be explained by the difference of heat capacity in surface materials.

2) Daytime

D1 and D2 in Fig. 5 show surface thermal images in the morning (about 10.40 JST) for the warm and cold period, respectively. Locations of noticeable cool spots are corresponding to the large green parks (Imperial Palace, Shinjukugyoen National Garden, etc.), where trees and grasses help to reduce the increasing of air temperature through evapotranspiration and also provide some shade with lower surface temperature (Fukui, 2003). Inside of designated urban zones surrounding urban center (Fig. 2), the surface temperature is also lower than outside and it is thought to be caused by the shading effect of tall buildings.

The surface temperatures of water areas are cooler than those of land areas in two seasons.

4.2 Effects of urban geometry on surface temperature

In order to examine the effects of urban geometry on the surface temperature, the correlation analyses were conducted. Fig. 6 shows the scatter diagrams between CRMBs and surface temperatures. The symbols in this figure correspond to those of the thermal images in Fig. 4. These graphs indicate that the land surface temperatures have strongly positive correlation with CRMBs in the evening (N1 and N2) and strongly negative correlation with CRMBs in the morning (D1 and D2). In all of 4 cases, their regression coefficients are statistically significant. Those regression equations indicate that the increase of tall buildings (CRMB) raises the surface temperatures in the evening and lowers them in the morning. The thermal effects with 10% increase of CRMB can be estimated $+0.24\degree C$, $+0.44\degree C$, $-0.47\degree C$, and $-0.50 \degree C$ for N1,N2,D1 and D2, respectively.

4.3 Effects of urban geometry on air temperature

1) Mean of daily minimum and maximum temperature distributions

Fig. 7 depicts the isotherms of mean minimum and maximum temperatures for the summers of 2003 and 2004. The summer of 2003 was cooler than normal and that of 2004, hotter than normal. For the minimum
temperatures (MN1, MN2), the warmer areas are expanded around the coastal area of Tokyo Bay, although the annual differences of temperatures exist. On the other hand, the hotter areas of maximum temperatures (MX1, MX2), seems to fan out from Urban Center to the north. The similarity of spatial distribution also appears between 2003 and 2004. These results, derived from the distributions of minimum and maximum temperatures, suggest that the spatial structure of temperature in the UHI of Tokyo strongly depends on the local condition of ground surface.

2) Effects of urban geometry on minimum and maximum temperature

The comparison between the minimum and maximum temperatures for each station of METROS100 and its surrounding CRMB were conducted. Then the correlations of the CRMBs with the mean minimum air temperatures were examined for two summers. Fig. 8 shows that the mean minimum temperatures are positively correlated with the CRMBs for 2003 and 2004. And their regression coefficients are statistically significant (p<0.01) both for summers. The negative correlations were found in case of the mean maximum temperatures, but the coefficients are not significant. Since the air temperature unlike the land surface temperature is susceptible to the wind, the sea breeze, that tends to occur in the early afternoon, is possible to mix the atmosphere around the city center. Therefore the negative correlations can suggest not only the shading effects of tall buildings but also the cooling effects of sea breeze.

3) Diurnal change in correlation coefficients between air temperatures and CRMBs

Fig. 9 illustrates the diurnal change in the spatial mean temperature and the correlation coefficients between the air temperature distribution and CRMB. For reducing the influence of wind and rain, we used the mean air temperatures derived from the data observed on the 6 days with weak wind and no-rainfall. The spatial mean temperature shows typical diurnal change. And the correlation coefficient harmoniously varies with the diurnal change of temperature, that is, the minimum temperature occurs with the largest positive correlation coefficient while the maximum temperature with negative one. And the absolute value of largest positive coefficient is much greater than that of negative one. Thus Fig. 9 indicates that the factor of urban geometry especially influences on the air temperature at night both through obstructing the release of long-wave radiation into the atmosphere and through increasing thermal storage capacity. However the cooling effects of shading by tall buildings is difficult to distinguish from those of sea breeze.

5. CONCLUSION

The following results were obtained from this study;
1) The coverage rate of mid-to-high-rise buildings is thought to be a good parameter indicating the urban geometry as like "Sky View Factor".
2) In the morning, land surface temperature is lower in the center of city than in the surroundings, but in the evening the temperature pattern is reversed.
3) The distribution patterns of land surface temperature are strongly correlated with the CRMB both in the evening and in the morning.
4) The distribution pattern of air temperature is significantly correlated with the CRMB in the evening, but not in the morning.
5) Urban geometry is thought to be one of the important factors that influence the thermal environment in Tokyo.

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REFERENCES