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Impacts of urban heat island mitigation strategies on surface temperatures in downtown Tokyo

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1. Introduction

Annual mean air temperatures in downtown Tokyo have already increased about 3 degrees Celsius (°C) in the past 100 years due to the global warming and urban heat island (hereafter, UHI), according to Japan Meteorological Agency. Also, in the Tokyo metropolitan area, heat wave and heat stroke frequencies tend to increase in recent years (e.g., Takaya et al., 2013; Takane et al., 2014). These have promoted implementation of UHI adaptation and mitigation strategies for summer heat in Tokyo. For instance, the Tokyo metropolitan government has made high-reflective and water retentive pavements as well as green and water spaces to improve outdoor thermal environment in downtown Tokyo. The improvement of thermal environment is one of the most urgent issues for the 2020 Summer Olympic and Paralympic Games, which will be held in Tokyo.

Effects of UHI adaptation and mitigation strategies for summer heat could be appreciated by reducing the corrected effective temperatures (CETs) that affect “feels like” temperatures. Values of CETs are determined by natural environmental factors: air temperature, humidity, wind speed, and radiant heat. It is difficult to control air temperature and humidity in outdoor spaces because those factors are strongly influenced by advection of air masses originating from synoptic-scale weather systems such as the north pacific high. Outdoor wind speeds can be controlled by changing urban geometry. Surface wind speeds would be increased in the area where a ventilation path is created. However, this would lead to decreases in wind speeds in its neighboring areas owing to the Bernoulli's principle. Artificial changes in wind speeds, thus, have strong trade-off relations unsuitable for government environmental measures. Compared with air temperature, humidity, and wind speed, amounts of radiant heat can be easily controlled by implementation of measures lowering surface temperatures with weak trade-off relations. Even if amounts of solar radiation and thermal infrared (TIR) energy radiated from land surfaces are decreased in a specific area, those in the neighborhood areas will not be increased. Reducing radiant heat is therefore considered to be suited for UHI adaptation and mitigation strategies.

This study performed airborne TIR measurements in summer in a broad area of downtown Tokyo at a lower flight level to obtain finer spatial resolution data. The data obtained were analyzed to show spatial variations of surface temperatures in midday on hot summer days and to discuss causes of the variations, using detailed land use/cover data. Changes in surface temperatures in Central Tokyo between two different years were also analyzed in this study. In Central Tokyo, incentive-based policies for improving environmental quality, which include UHI adaptation and mitigation strategies, have been actively implemented in recent years.

2. Data and methods

We performed airborne measurements of amounts of TIR energy emitted from urban surfaces in downtown Tokyo, using a TIR imaging camera (Nippon Avionics Co., Ltd.; TS7302) installed on a Robinson R22 helicopter. The camera can detect infrared radiation at wavelengths of 8-14 μm . The airborne TIR measurements were carried out between 12 and 13 local time (LT: coordinated universal time plus 9 hours) on the three different hot summer days: August 7, 2007 (M2007), August 19, 2013 (M2013), and August 19, 2014 (M2014). In those measurements, visible images were acquired simultaneously, using a high definition camera.

As shown in Figure 1, M2007 and M2013 were conducted in Central Tokyo and its surrounding areas. M2014 was conducted in Shinjuku subcenter of Tokyo and its surrounding areas. The gross area in all the measurements is about 5,000 ha. Despite highly developed urban areas including several skyscrapers, the helicopter was flying at Flight Level 20 (2,000 ft, i.e., 610 m). The lower flight level allows horizontal spatial resolutions of data obtained from the TIR imaging camera to be approximately 2 m. The imaging data obtained were geometrically corrected by orthorectification to remove effects of image perspective as much as possible, based on ground control points. In addition, latitude and longitude geographic coordinates were given to the corrected imaging data.

As shown in Table 1, surface weather conditions on the three days were quite similar. Southerly sea breezes prevailed in downtown Tokyo on those days. Prior to M2013, abnormally hot weather conditions persisted after August 7. A clear sky without any clouds was predominant over downtown Tokyo in a period of M2013. In periods of M2007 and M2014, some small cumulus clouds associated with the elevated mixed layer appeared sporadically. However, the airborne TIR measurements are hardly obstructed by the cumulus clouds because the flight level is

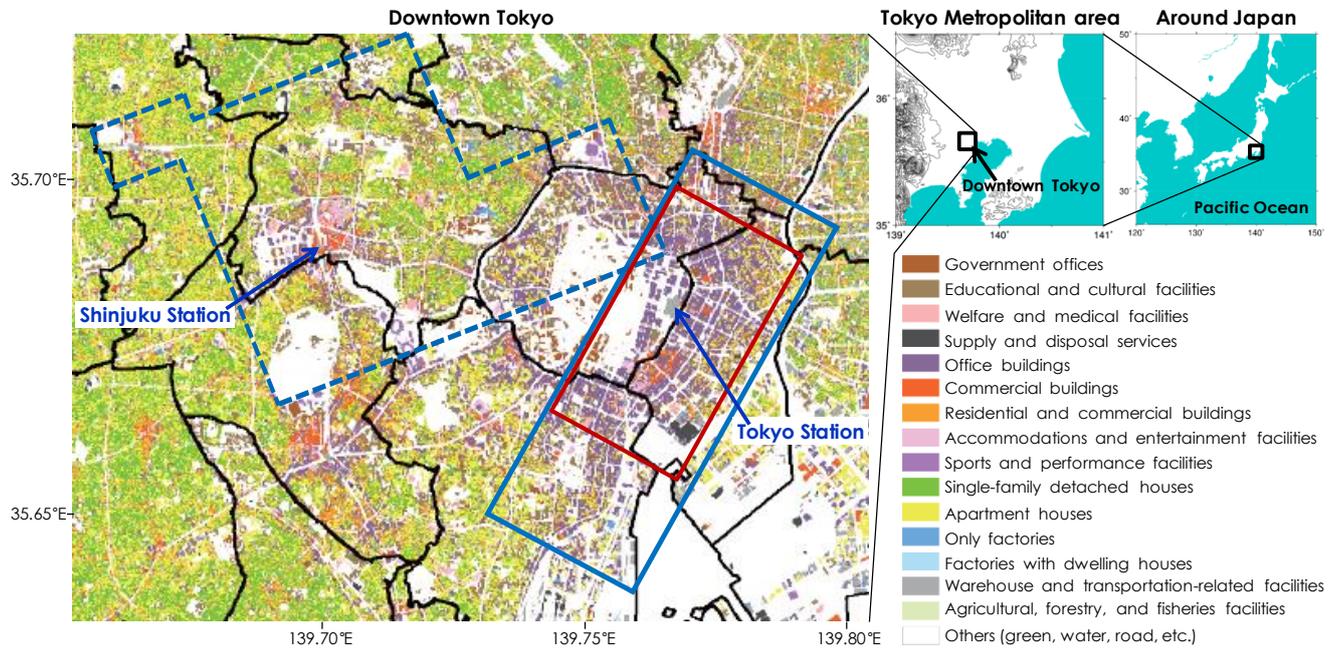


Fig. 1 Land uses/covers in downtown Tokyo. The red and blue boxes indicate the domains of M2007 and M2013, respectively (Central Tokyo and its surrounding areas). The thick broken blue lines indicate the domain of M2014 (Shinjuku subcenter of Tokyo and its surrounding areas). The thick solid black lines indicate municipal boundaries.

Table 1 Surface weather conditions at Central Tokyo at 1200 LT. (data from Japan Meteorological Agency.).

Date	Air Temperature	Global Solar Radiation	Relative Humidity
	°C	MJ/m ²	%
Aug. 7, 2007	32.0	3.10	50
Aug. 19, 2013	33.1	3.11	58
Aug. 19, 2014	33.3	3.17	55

almost below the cloud bases.

The higher relative humidity and sea breeze conditions indicate that outgoing TIR radiation was attenuated by the abundant water vapor in the lower troposphere before reaching the airborne TIR imaging camera. Absolute values of amounts of TIR energy obtained from the airborne measurements would therefore be different from those observed by ground-based measurements. However, the aim of this study is not estimations of absolute values of TIR energy but investigations of the spatial and temporal changes in TIR energy. Since it is not necessarily have to use the absolute values for such investigations, this study analyzes amounts of attenuated TIR energy. Also, Table 2 shows values of relative humidity ranges from 50% to 58%, indicating that differences in atmospheric attenuation of TIR energy among M2007, M2013, and M2014 are negligible.

In this study, the attenuated amounts of TIR energy were converted to land surface temperatures by the Stefan-Boltzmann law, assuming land surface emissivity to be 1.

3. Results and discussions

Figure 2 shows a *visible image and surface temperatures* in Shinjuku subcenter of Tokyo and its surrounding areas, derived from results of M2014. A comparison of Figure 2b with Figure 1 indicates relatively high surface temperatures in the areas classified as “single-family detached houses” (light-green colored areas in Figure 1), compared with those in areas with other land uses/covers such as the “office buildings” and “commercial buildings”. In downtown Tokyo, high density wooden houses are located in the areas with single-family detached houses. Since the heat capacity of wooden houses is much small, the roof surface temperatures appear to tend to easily increase under large amounts of solar radiation on sunny days. Also, there is a possibility that the high density

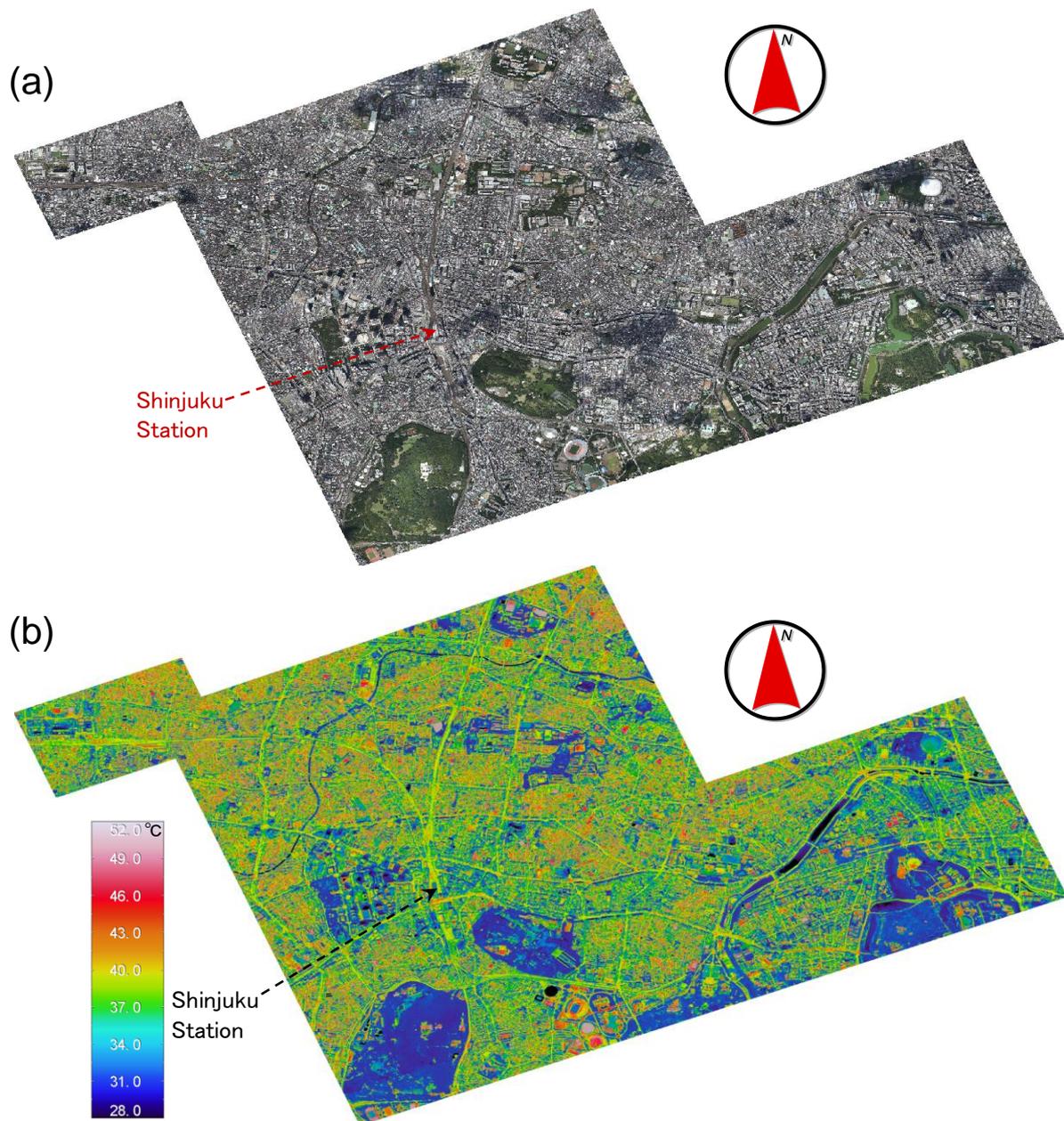


Fig. 2 (a) Visible image and (b) distribution of surface temperatures in the area enclosed by the thick broken blue lines in Fig. 1, obtained from M2014.

houses reduce wind velocities near the surfaces, thereby decreasing sensible and latent heat fluxes that would be increased by stronger surface winds. Assuming that subsurface heat fluxes are constant, the decreases in sensible and latent heat fluxes might lead to increases in amounts of TIR energy emitted from surfaces.

These support the results of Ando et al. (2009) and Li et al. (2011), which showed that areas with high-rise buildings have lower surface temperatures than its surrounding areas with low-rise buildings such as residential houses, indicating large effects of urban geometry and land use/cover characteristics on UHIs.

Figure 3 shows surface temperatures in the domain represented as a red box in Figure 1, obtained from M2013 and M2007. Also, Figure 4 shows differences in surface temperatures between M2013 and M2007 in the same domain. Since abnormally hot weather conditions persisted in the period prior to M2013, surface temperatures obtained from M2013 are relatively large in the greater part of the domain, compared with those from M2007. However, in several places, surface temperatures obviously decrease between 2007 and 2013 (Figure 4). Especially, the decreases in surface temperatures are remarkable in the renewal areas marked “R1” and “R2” in Figures 3-4. The R1 and R2 indicate the “Otemachi-Marunouchi” and “Ochanomizu” areas, respectively. In those areas, several new buildings were completed between 2007 and 2013 with about 2,000,000 m² total floor area increases.

Visible images and surface temperatures in parts of the areas R1 and R2 in Figure 3a, obtained from M2013, are shown in Figure 5. These images are the original versions before removing perspective projection distortion by orthorectification. In this figure, green surfaces can be seen in public open spaces with the comparatively low surface temperatures (see areas enclosed by the dotted lines).

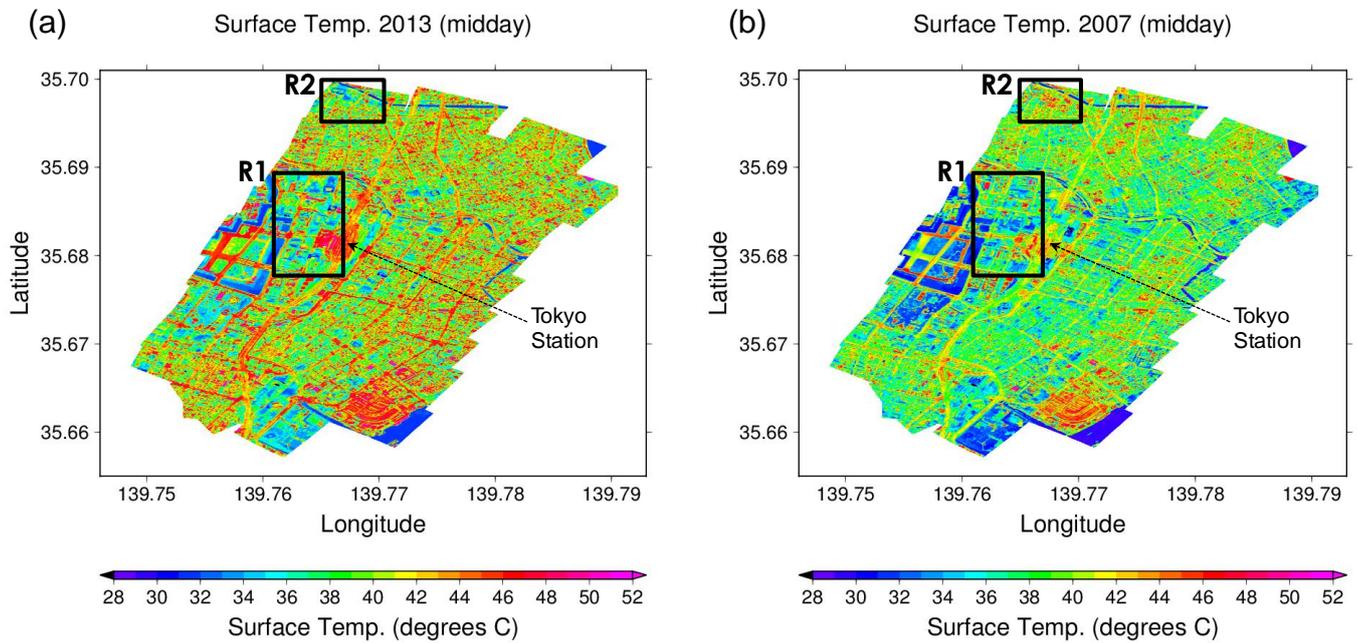


Fig. 3 Surface temperatures in the red box in Figure 1, obtained from (a) M2013 and (b) M2007. The boxes marked “R1” and “R2” represent the two renewal areas: “Otemachi-Marunouchi” and “Ochanomizu”, respectively.

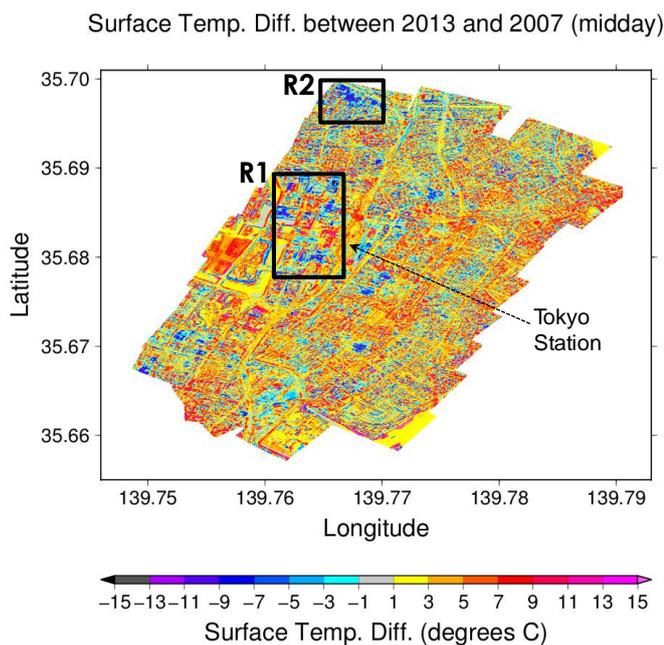


Fig. 4 Differences in surface temperatures between M2013 and M2007.

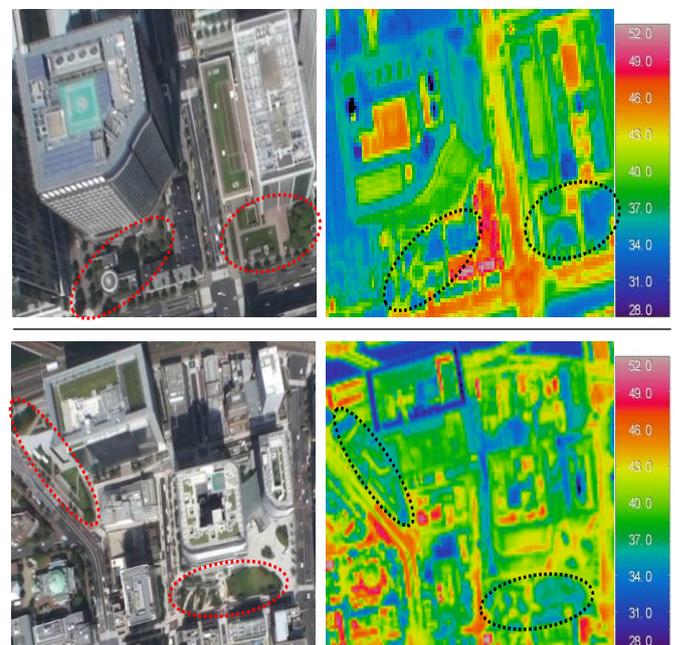


Fig.5 Visible images and surface temperatures in a part of R1 (upper panels) and R2 (lower panels) (M2013).

The remarkable decreases in surface temperatures in the renewal areas are considered to be due to an incentive-based policy enacted by the Tokyo metropolitan government as part of environmental protection, disaster prevention, and UHI adaptation and mitigation strategies. As shown in Figure 6, the Tokyo metropolitan government has promoted creation of public open spaces in the renewal areas by enacting the incentive policy that enable to increase the floor area ratios as a bonus. In the public open spaces created, many green surfaces have been provided. This would cause the decreases in surface temperatures in the renewal areas.

4. Summary and conclusion

To investigate spatial and temporal changes in surface temperatures in downtown Tokyo in midday and their relations to land use/cover variations, 2 m spatial resolution data obtained from lower flight level airborne measurements of TIR energy were analyzed in this study. The airborne measurements were performed in 12-13 LT on the three different hot days: August 7, 2007, August 19, 2013, and August 19, 2014. Surface weather conditions on those days were quite similar. The results showed that surface temperatures are especially large in the areas classified as single-family detached houses where high density wooden houses are located, compared with those in the areas with office and commercial buildings.

As a result of analyses of differences in surface temperatures between 2013 and 2007, we found remarkable

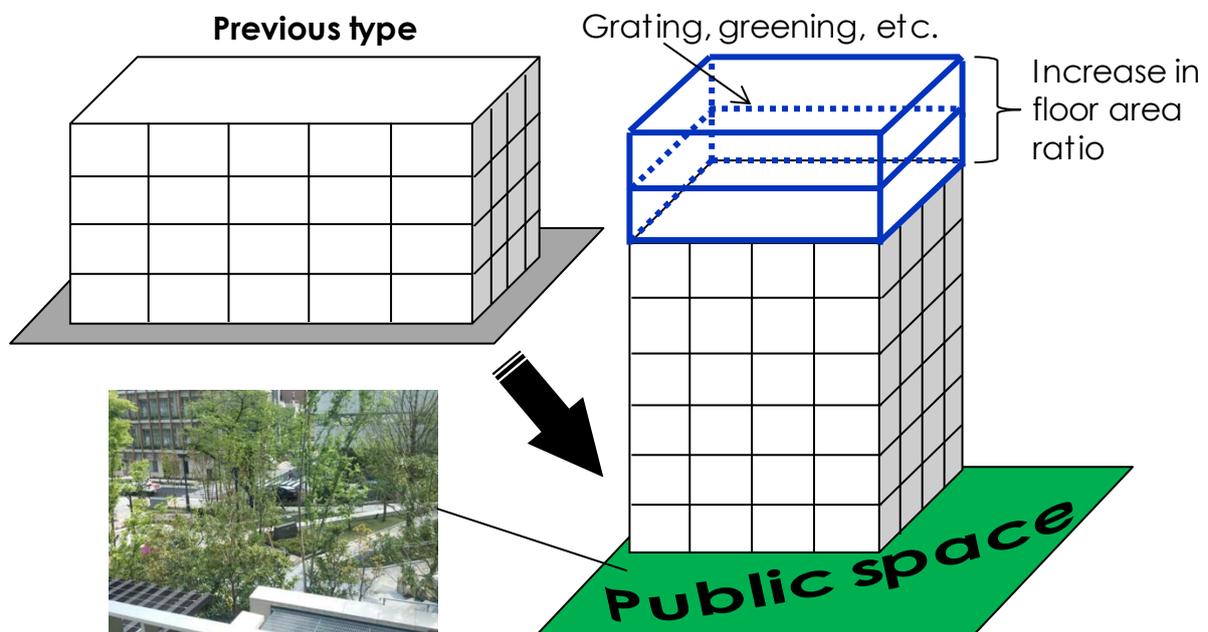


Fig. 6 Conceptual figure of an incentive-based policy enacted for improving environmental quality in downtown Tokyo. The picture was taken at a public open space in the Ochanomizu area ("R2" in Figures 3-4).

decreases in surface temperatures in renewal areas: "Otemachi-Marunouchi" and "Ochanomizu" where many green surfaces have been provided in public open spaces. In the areas with office and commercial buildings, creation of public open spaces was promoted by an incentive-based policy that enables to increase the floor area ratios as a bonus. The incentive-based policy was enacted by the Tokyo metropolitan government as part of environmental protection, disaster prevention, and UHI adaptation and mitigation strategies.

On the basis of these results, this study strongly suggests that some governmental measures like the incentive system enacted for the areas with office and commercial buildings are required to decrease the daytime high surface temperatures in the high density wooden residential areas as part of UHI adaptation and mitigation strategies. For instance, the practice of growing and cultivating plants by gardening and installations of high-reflective roofs would be effective in reducing the daytime radiant heat there, in addition to solution of the high density housing conditions in the areas.

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