The effects of citizen-driven urban forestry on summer high air temperatures over the Tokyo metropolitan area

Yuji Masutomi\textsuperscript{a}\textsuperscript{b}, Yousuke Sato\textsuperscript{b}, Atsushi Higuchi\textsuperscript{c}, Akinori Takami\textsuperscript{d} and Teruyuki Nakajima\textsuperscript{e}

\textsuperscript{a}Graduate School of Agriculture, Ibaraki University, Inashiki, Ibaraki, Japan  
\textsuperscript{b}Department of Earth and Planetary Sciences, Faculty of Science, Hokkaido University, Sapporo, Hokkaido, Japan  
\textsuperscript{c}Center for Environmental Remote Sensing, Chiba University, Chiba, Chiba, Japan  
\textsuperscript{d}National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan  
\textsuperscript{e}Earth Observing Research Center, Japan Aerospace Exploration Agency, Tsukuba, Japan

Abstract

In urban areas around the world, air temperature increases due to global warming and urbanization are adversely affecting human health and living environments. We used a numerical weather forecasting model to quantitatively simulate the effectiveness of citizen-driven urban forestry, the voluntary activity of citizens to plant and maintain trees in their residential areas, as a method for reducing summer air temperatures in the Tokyo metropolitan area, the largest urban area in Japan. We calculated the daily maximum air temperature for 10 days in the summer of 2007, and simulated the effects of five different levels of increased urban forest area per capita according to population distribution using albedo, heat capacity, and evapotranspiration. Increasing the forest cover by 3.3 m\textsuperscript{2} per capita reduced the daily maximum air temperature by only 0.014 \degree C, although the effect increased linearly with higher forest cover per capita. If forest planting is increased to about 30 m\textsuperscript{2} per capita, the air temperature reduction in the center of Tokyo could reach 0.4 to 0.5 \degree C, comparable to the increase in urban air temperature over the past hundred years due to global warming. The results suggest that the collective actions of individual citizens to increase urban forest cover can produce a significant effect on the mitigation of high air temperatures due to the urban heat island effect and climate change.

Key words: Citizen-driven urban forestry, Global warming, Tokyo, Urban heat island, Weather simulation

1. Introduction

The urban heat island (UHI) effect has appeared in urban areas around the world (Zhou \textit{et al.}, 2004; Stone, 2007; Fujibe, 2009; Peng \textit{et al.}, 2012) and affects urban residents, who account for approximately half of the global population (United Nations, 2014). These high air temperatures have direct and indirect serious and harmful effects on urban citizens’ lives, including increased rates of mortality, heat attacks, and other health effects related to increased ozone concentrations near the land surface (Krupnick \textit{et al.}, 1990; Lippmann, 1993; Rosenfeld \textit{et al.}, 1998). For example, in the Tokyo metropolitan area (TMA, the largest urban area in Japan), over 2000 people were hospitalized for heat stroke during the summer of 2010 (FDMA, 2019). As these impacts are expected to increase in the future due to global warming and urbanization (Stocker \textit{et al.}, 2013), the reduction of high urban air temperatures is an important political challenge for urban governments around the world.

Several measures intended to mitigate high urban air temperatures have been proposed, such as increasing roof albedo (Krayenhoff and Voogt, 2010), changing pavement materials (Takebayashi and Moriyama, 2012), modifying urban structures (Scherer \textit{et al.}, 1999), and adding vegetation to building rooftops (Onishi \textit{et al.}, 2010). Urban greening by planting trees, often called urban forestry (UF), has been widely adopted around the world (Salbitano \textit{et al.}, 2016) because the efficacy of UF for air temperature reduction has been proven through many observations (e.g., Ca \textit{et al.}, 1998; Yu and Hien, 2006) and numerical simulations (e.g., Tong \textit{et al.}, 2005). Some aspects of the physical mechanisms of UF for air temperature reduction are well understood, including increased evapotranspiration (Huang \textit{et al.}, 1990) and increased albedo (Akbari \textit{et al.}, 1997). In addition, this practice can result in many other benefits, including increasing carbon sinks, decreasing energy consumption, improving air quality, and conserving biodiversity (Salbitano \textit{et al.}, 2016).

However, the implementation and maintenance of UF is very costly. McPherson \textit{et al.} (2005) estimated that the annual cost of planting and maintaining a tree in five American cities ranged from $13 per tree in Glendale to $65 per tree in Berkeley, California. This means that a local government could pay about $6.5 million to plant and maintain a 10\textsuperscript{2} m\textsuperscript{2} (100 ha) urban forest, assuming that an individual tree covers 10 m\textsuperscript{2}. Such an investment would be difficult for most local governments, although UF can produce a range of benefits.

Citizen-driven urban forestry (CDUF), the voluntary activity of citizens to plant and maintain trees in their residential areas, has been implemented in several pioneering cities as an alternative to government-led approaches (e.g., City of
Cambridge, 2015; TreePeople, 2016). For example, Saitama prefecture, located in the northern part of the TMA, began implementing CDUF in 2009 in order to address the seriously high summer air temperatures produced by drastic urbanization over the last three decades (Saitama Pref., 2017).

However, it is unknown how much UF area per capita is required for effective reduction of high air temperatures. Scientific answers to these questions would help local governments and non-governmental organizations (NGOs) make decisions with regard to implementation, promotion, or discontinuation of CDUF initiatives. In this context, our study investigated whether CDUF is effective for reducing high air temperatures and to what extent UF area per capita must be increased for effective air temperature regulation. We investigated these aspects by conducting numerical simulations with a meteorological model, focusing on the TMA, where air temperature has increased due to rapid urbanization and global warming (Fujibe, 2009).

2. Methods and data

2.1 Experimental framework

To quantitatively assess the effects of CDUF on urban air temperature reduction, we simulated air temperatures at 2 m above the ground ($T_s$) using a meteorological model (Japan Meteorological Agency Non-Hydrostatic Model; JMANHM: Saito et al., 2006). First, we checked the model’s performance for simulations of $T_s$ by comparing observed and simulated $T_s$ under current conditions of land-use and land-cover (LULC). Next, we quantitatively assessed the effects of increased UF per capita on air temperature by comparing the values of $T_s$ modeled under five different LULC conditions corresponding to a simulated increase in UF of 3.3, 9.9, 16.5, 23.1, and 29.7 m$^2$ per capita ($UF_{pc}$) according to population distribution, respectively. The unique aspect of this study compared to earlier work on the effects of UF pertains to its assessment of the effects of CDUF by increasing UF according to the population distribution. We assumed that the trees in a forest covering a target area of 200 km $\times$ 200 km (covering the TMA, Fig. 1) are planted in the simulations; technically, these trees comply with the parameters for “Forest,” as explained in Section 2.3. The simulations were conducted for the period of 7–17 August 2007, which coincided with the highest air temperature records in this area (JMA, 2008).

2.2 JMANHM and simulation setting

We used the JMANHM (Table 1) developed by the Japan Meteorological Agency (JMA) to simulate $T_s$ because it was used as the operational model for Japanese weather forecasting until it was replaced by a new non-hydrostatic model, ASUCA (JMA, 2014), in February 2017. Therefore, it can be expected to produce highly accurate results. The simulations were conducted with a time step of 3 s over a period of 10 days, from 00:00 UTC on 7 August, 2007 to 00:00 UTC on 17 August, 2007. We analyzed the results of the final 9 days to avoid any artificial effects from the initial conditions. The horizontal grid resolution was 1 km ($200 \times 200$ grid points), and 40 vertical layers existed from the surface to the top of the model at 22400 m. The vertical grid resolution was stretched from 40 m (first layer of the model) to 1120 m (the top of the model). To calculate $T_s$ from air temperature in the first layer, we used the methods previously described by Adachi et al. (2014).

For a land surface model, we used the SLAB model (Hara et al., 2008), which was implemented in JMANHM and the new non-hydrostatic model, ASUCA. In the SLAB model, a land surface is represented as a plane, and the energy balance at the plane is solved without considering plant and urban canopies. Additionally, the original SLAB model distinguished only two types of land surfaces: with snow and without it. To represent the differences among several LULC types in the SLAB model, we assigned different values for the land parameters, namely, albedo ($\alpha$), evaporation coefficient ($\beta$), and heat capacity ($C_h$), to each type of LULC (Table 2). We used the method in Sato et al. (2016), where the parameter values are determined based on

![Study area with named prefectures in the Tokyo Metropolitan Area and elevation in meters.](image)

**Table 1. Model components.**

| Name and Reference |
|--------------------|
| Governing equation system | Compressible |
| Grid system (Terrain) | Arakawa-C (Terrain-following: Gal-Chen and Somerville, 1975) |
| Time discretisation | Horizontally explicit and vertically implicit (HE-VI) |
| Spatial discretisation | 4th order central differential scheme (Kato, 1998) |
| Cloud microphysics | 1-moment bulk microphysical scheme (Yamada, 2003) |
| Turbulence scheme | Mellor-Yamada type level 2.5 (Nakanishi and Niino, 2006) |
| Surface flux | Louis type scheme with bulk coefficient of Land (Louis, 1979) and sea surface (Kondo, 1975) |
| Radiation | Kitagawa’s scheme (Kitagawa, 2000) |
Kondo (1994). For the other land parameters, we used default values for the land and sea of the SLAB model in JMANHM (e.g., roughness lengths were 0.1 m for land and 0.01 m for sea, and emissivity of the land surface was 1.0 for all areas).

The JMA operational mesoscale analysis (JMA-MANAL) was used for the initial and boundary conditions of the model (i.e., horizontal wind velocity, pressure, potential temperature, and relative humidity). The vertical wind velocity was set as 0 at the initial time and lateral boundary. The sea surface temperature data were sourced from reanalysis data of the National Center for Environmental Prediction (NCEP: Kalnay et al., 1996). The model’s topography was drawn from the GTOPO 30 data set (USGS, 1996). Note that anthropogenic heat was not considered in the simulations.

2.3 Land parameters

We based the control LULC of each grid box (i.e., with no trees added) on data from the Ministry of Land Infrastructure and Transport (MLIT, 2006), which consists of numerical data for eleven LULC types. However, the model used in this study only considered five LULC types (Table 2). Thus, we reassigned the eleven MLIT types to match the five types in the model (Table 3). We then calculated the mean values of the three parameters (albedo, heat capacity, and evapotranspiration) for each grid point in the simulations, using the area fraction of each LULC type to calculate a weighted average. The spatial resolution of the MLIT data was approximately 1 km, but the grids of the MLIT data do not match those of the simulations. Thus, we transformed each grid of the MLIT data into the simulation grids, using the nearest neighbor method. Note that a simpler method than a previous study (Sato et al., 2016) was used for the LULC assignment. Therefore, the control LULC condition in the present study is different from the control simulation in Sato et al. (2016).

For each model run, in which the UF area per capita was increased by 3.3, 9.9, 16.5, 23.1, and 29.7 m$^2$, respectively, the values of the land parameters for each 1 km grid box were set by converting urban area to forested area based on population data (MIAC, 2005; Fig. 2) and calculating the values of land parameters for each grid box as described above. We assumed that only up to 40% of the urban area in each grid box could be converted to forested area, since the ability to plant trees in urban areas is limited (Sato et al., 2016). Any forested area over this limit was added to the grid box with the largest urban area among the eight neighboring grid boxes. The resulting forested areas are shown in Figs. 3 and 4, which indicate that the forested area gradually, but clearly, increases with increasing UF$_{pc}$. The increases in Tokyo, Saitama, and Kanagawa are especially clear due to their large urban areas and populations.

3. Results

3.1 Model validation

In order to evaluate the model, we conducted comparisons of the modeled $T_\text{s}$ and observations from the Automated Meteorological Data Acquisition System (AMeDAS), a network of Japanese weather stations. Since this study focused on high air temperature in summer, we only analyzed the daily maximum $T_\text{s}$ ($T_{\text{s, max}}$). Figure 5 shows a scatter plot of $T_{\text{s, max}}$ between the simulations and 378 data points drawn from 9 days
of observations at 42 stations. The observed $T_{\text{max}}$ data were well reproduced by the model, with a mean error and correlation coefficient of $-0.58$ °C and 0.884, respectively, although the model did underestimate $T_{\text{max}}$ at air temperatures over 36 °C and below 33 °C.

In order to investigate this pattern of underestimation, we plotted the horizontal distribution of $T_{\text{max}}$ (Fig. 6). The underestimation at high air temperatures is evident in the northwestern part of the study area (e.g., Saitama and Gunma prefectures). The air temperatures of over 35 °C observed in this area mainly originated from foehn-type winds carrying warm, dry air from mountain ranges to this area (Sakurai et al., 2009), but the model domain was not wide enough to reproduce these wind patterns (as discussed by Sato et al. (2016)), resulting in the apparent underestimation. The underestimation at low air temperatures is mostly seen in the southern and eastern parts of the study area, which are located near the sea and the edge of the study area. The underestimation can be attributed to the effects...
of the sea and edge. In spite of this problem, the regional contrast in $T_{\text{max}}$ between the coastal and inland areas is well-reproduced.

To confirm whether the model can simulate the influence of the increase in UF on surface air temperature, we compared the relationship for simulations and observations between $T_{\text{max}}$ and the ratio of forest area in a grid box where each AMeDAS station is located. In this comparison, we focused on the AMeDAS stations whose altitude is less than 100 m to exclude the effect of decrease in air temperature due to high altitude, where the ratio of forest area is usually high. Figure 7 shows the relationship for simulations and observations between $T_{\text{max}}$ averaged over the last 9 days of the simulation period and the ratios of forest area around the AMeDAS stations. Linear regressions show that average $T_{\text{max}}$ decreases as the ratio of forest area increases, and that the simulated slope was similar to the observed values.

### 3.2 Effects of CDUF

In this section, we discuss the values of $T_{\text{max}}$ under the different UF scenarios. Before analyzing the effect of UF, we re-gridded the 1 km × 1 km (200 × 200) grids to 5 km × 5 km (40 × 40 = 1600) grids by averaging values of the former. Figure 8 shows $T_{\text{max}}$ averaged during the last 9 days of the simulation period for the grid boxes in which the forested area was increased under the scenario of the increase in UF by 3.3 m$^2$ per capita from the control (767 out of 1600 grids). The averaged $T_{\text{max}}$ clearly decreased with increasing $UF_{pc}$. The relationship between averaged $T_{\text{max}}$ and the increase in $UF_{pc}$ ($IUF_{pc}$) obtained from regression analysis is as follows:

$$T_{\text{max}} = -0.00379 \cdot IUF_{pc} + 33.13 \quad \text{(adjusted - } R^2 = 0.998).$$

Following this equation, the averaged $T_{\text{max}}$ decreases by 0.00379 °C with an increase in $UF_{pc}$ of 1 m$^2$ per capita.

In addition, the spatial distribution of the difference in $T_{\text{max}}$ from the control ($\Delta T_{\text{max}}$) is useful for understanding the effects of increased urban forest cover. As shown in Fig. 9, minor

---

**Fig. 5.** Scatter plot between $T_{\text{max}}$ simulated by the model and that observed by the AMeDAS weather stations in the study area.

**Fig. 6.** $T_{\text{max}}$ averaged over 9 days (from 8–17 August 2007) (a) observed by AMeDAS weather stations, (b) simulated by the model, and (c) difference between (a) and (b).

**Fig. 7.** Relationship between observations (AMeDAS; black points and line) and simulations (red points and line) between the averaged maximum air temperature ($T_{\text{max}}$) and the ratio of forest area in a grid box where the AMeDAS stations are located.
increases in $UF_{pc}$ have only slight impacts on $T_{\text{max}}$, but as $UF_{pc}$ increases, the effect becomes clear, and the area with reduced $T_{\text{max}}$ enlarges significantly (Fig. 9b-e). If $UF_{pc}$ is increased by 29.7 m² per capita, as in Fig. 9e, $T_{\text{max}}$ decreases over most of the TMA, with a $\Delta T_{\text{max}}$ of $-0.5$ to $-0.4$ °C in the center of the TMA. The response of $T_{\text{max}}$ was not consistent over the ocean, likely due to the effects of the model’s lateral boundary, to which artificial damping was applied for model stability. This area can be ignored for the purpose of this analysis.

In order to clarify how areas with negative $\Delta T_{\text{max}}$ were broadened by increasing $UF_{pc}$, we plotted the relationship between the ratio of grid points with negative $\Delta T_{\text{max}}$ and the increase in $UF_{pc}$ (Fig. 10). Note that this analysis considered grids where the forested area was increased under the scenario in which $UF$ was raised by 3.3 m² per capita compared to the control. $T_{\text{max}}$ was reduced in about 70% of the grid boxes under the 3.3 m² $IUF_{pc}$ condition, but this value increased to over 90% under the 29.7 m² $IUF_{pc}$ condition. The ratio of the grid points with negative $\Delta T_{\text{max}}$ clearly increased with increasing $UF_{pc}$.

Notably, $T_{\text{max}}$ increased in about 7% of the grid boxes even under the highest increase in $UF_{pc}$, and this can be attributed to the nearshore and offshore increase in $T_{\text{max}}$, as discussed above.

Figure 11 shows the relationship between $\Delta T_{\text{max}}$ and the ratio of the increase in the urban forest area (not $UF_{pc}$ itself) to the area of each grid box. As this ratio increases, $T_{\text{max}}$ declines in a linear fashion with a slope (obtained by regression analysis) of $-1.02$. This means that $T_{\text{max}}$ reduced by about 0.1 °C due to an increase in urban forest area, corresponding to 10% of a grid box’s area.

4. Discussion

4.1 Effective levels of CDUF

Having shown that increases in urban forest can lower air temperatures in general, we now consider how much UF area per capita is required to be increased for effective reduction in high air temperatures. As shown above, an increase of 3.3 m² per capita in urban forest cover produces only a 0.014 °C change in air temperature (Fig. 8), while the spatial effect on $T_{\text{max}}$ is not clear in this case (Figs. 9a and 10). Sato et al. (2016) used the same weather model to show that changing urban structures and greening at large scales could result in $\Delta T_{\text{max}}$ values of $-0.043$ to $-0.073$ °C, and Adachi et al. (2014) reported that the “compact city” of Tokyo could reduce night air temperatures in urban areas by 0.1 °C, using a weather model considering urban canopies. Thus, the effects of small-scale CDUF are lower than results
of Tokyo has increased by 3.1 °C during the last hundred years. Yoshida et al. (2002) used computational fluid dynamics to show that artificial exhaust heat can increase the UHI in Tokyo by up to 1.5 °C. Fujibe (2009) also compared increases in air temperature between urban and rural areas to show that global warming has contributed to an increase in $T_s$ of 0.6 °C in urban areas; thus, the increase in $T_s$ due to global warming is similar to the reduction in $T_s$ produced in the center of Tokyo by an increase in $UF_{pc}$ of 29.7 m² per capita. Therefore, we can conclude that increasing urban forest cover can effectively reduce summer high air temperatures if the increase in $UF_{pc}$ is large enough, for example, over 16.5 m² per capita. In addition, by combining urban forestry with large-scale changes in urban structure, it could be possible to obtain even larger reductions in air temperatures.

### 4.2 Uncertainties, limitations, and challenges

There are several uncertainties, limitations, and challenges related to this study. First, the assumption of the potential maximum UF area ratio, which we set at 40%, is one of the major uncertainties. This value is dependent upon several factors, including urban structures and the types of trees planted. In areas with buildings, it may be necessary to introduce greenery on rooftops instead of growing trees (Santamouris, 2014). However, it is difficult to accurately estimate these factors over a large area, and thus, we set our limit at 40% following Sato et al. (2016). Future studies could explore different values for this limit in order to improve the accuracy of the results.

Second, similar to all weather models, the JMANHM model itself has some uncertainty regarding the estimation of air temperature, which is caused by uncertainties in model parameters and structures. Especially, the values of land surface parameters have an influence on the simulation results. For example, Sato et al. (2016) showed that the increase in the value of albedo had a large cooling effect. Ensemble simulation using multiple weather models with multiple values for model parameters is a useful approach for estimating the range of uncertainty, which itself provides useful information for policy-makers. Therefore, multi-ensemble simulations should be used in future studies to further assess the accuracy of these results.

Third, it might be possible to improve the accuracy of the effect of UF in the simulation by using advanced models that consider detailed physical and biological processes in urban areas. In the present study, we simulated the effect of UF using the SLAB model as a land surface model. Even though the SLAB model is relatively simple, the accuracy of the model to simulate air temperatures and the effect of forested area on air temperatures were high and sufficient for the scope of the present study (Section 3.1). However, some advanced models have considered urban canopies (e.g., Kusaka et al., 2001; Lee and Park, 2008) and the interaction between buildings and forests in urban areas (e.g., Krayenhoff et al., 2014, 2015; Ryu et al., 2016). These advanced models for urban simulations could help improve the simulation accuracy and our understanding of the effect of UF.

In spite of these uncertainties and limitations, this study is a meaningful first step toward estimating the effects of increased
UF on high air temperatures and supplying useful quantitative results that can guide local governments and other organizations in planning mitigation interventions for high urban air temperatures.

5. Conclusions

In this study, we modeled the effects of increasing urban forest cover on air temperature using a Japanese operational meteorological model (JMANHM) in order to assess whether CDUF is effective at reducing high air temperature and the extent to which urban forest area per capita should be increased for effective results.

The results of the model suggest that CDUF is not effective for the reduction of high air temperatures if the increase in \( U_{\text{fe}} \) is small. However, it is effective for the reduction of high air temperature if the increase in \( U_{\text{fe}} \) is large enough, for example, 16.5 m² per capita or more. These results suggest that the collective actions of individual citizens within a CDUF framework could have a significant impact on the mitigation of high urban air temperatures. Although further research should be conducted to improve the reliability of our estimates, these results provide useful quantitative information for local governments and organizations considering the implementation of CDUF.

Acknowledgements

This study was supported by the Global Environment Research Fund S-12 of the Ministry of the Environment (MOE) in Japan, NIES/GOSAT, NIES/CGER, and MEXT/RECCA/SALSA.

References

Adachi SA, Kimura F, Kusaka H, Duda MG, Yamagata Y, Seya H, Nakamichi K, Aoyagi T, 2014: Moderation of summertime heat island phenomena via modification of the urban form in the Tokyo metropolitan area. *Journal of Applied Meteorology and Climatology* 53, 1886–1900. DOI: 10.1175/JAMC-D-13-0194.1

Akbari H, Bretz S, Kurn DM, Hanford J, 1997: Peak power and cooling energy savings of high-albedo roofs. *Energy and Buildings* 25, 117–126. DOI: 10.1016/S0378-7788(96)01001-8

Ca VT, Asaeda T, Abu EM, 1998: Reductions in air conditioning energy caused by a nearby park. *Energy and Buildings* 29, 83–92. DOI: 10.1016/S0378-7788(98)00032-2

City of Cambridge, 2015: Cambridge Urban Forest Plan, 133 pp. Available online: https://www.cambridge.ca/en/learn-about/resources/Accessible-PDFs/Cambridge-Urban-Forest-Plan-2015-2034.pdf

Fire and Disaster Management Agency (FDMA), 2019: Data on the Number of Heat Stroke Patients Transported to Hospital by Ambulance (in Japanese). Available online: https://www.fdma.go.jp/disaster/heatstroke/post3.html

Fujiibe F, 2009: Detection of urban warming in recent temperature trends in Japan. *International Journal of Climatology* 29, 1811–1822. DOI: 10.1002/joc.1822

Gal-Chen T, Somerville RC, 1975: On the use of a coordinate transformation for the solution of the Navier-Stokes equations. *Journal of Computational Physics* 17, 209–228. DOI: 10.1016/0021-9991(75)90037-6

Hara T, Oizumi M, Miura D, 2008: Land surface process (in Japanese). *JMA Numerical Prediction Division Report* 54, 166–194.

Huang YJ, Akbari H, Taha H, 1990: The wind-shielding and shading effects of trees on residential heating and cooling requirements. *Proceedings of the ASHRAE Winter Conference*, Atlanta, GA (USA), p. 11–14.

Japan Meteorological Agency (JMA), 2008: *Climate change monitoring report 2007*. Available online: http://www.jma.go.jp/jma/en/NMHS/ccmr/CCMR2007.pdf

Japan Meteorological Agency (JMA), 2014: Next generation Non-Hydrostatic Model: asuka. *JMA Numerical Prediction Division Report* 60.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Kettmaia A, Reynolds R, Jenne R, Joseph D, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society* 77, 437–471. DOI: 10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

Kato T, 1998: Numerical simulation of the band-shaped torrential rain observed over southern Kyushu, Japan on 1 August 1993. *Journal of the Meteorological Society of Japan* 76, 97–128. DOI: 10.2151/jmsj.65.1-97

Kitagawa Y, 2000: Radiation process. *JMA Numerical Prediction Division Report* 46, 16–31 (in Japanese).

Kondo J, 1975: Air-sea bulk transfer coefficients in diabatic conditions. *Boundary-Layer Meteorology* 9, 91–112. DOI: 10.1007/BF00232256

Kondo J, 1994: *Meteorology of Water Environment*, 1st ed. Asakura Publishing Co., Ltd. (in Japanese).

Krayenhoff ES, Voogt JA, 2010: Impacts of urban albedo increase on local air temperature at daily–annual time scales: model results and synthesis of previous work. *Journal of Applied Meteorology and Climatology* 49, 1634–1648. DOI: 10.1175/2010JAMC2356.1

Krayenhoff ES, Christen A, Martilli A, Oke TR, 2014: A multi-layer radiation model for urban neighbourhoods with trees. *Boundary-Layer Meteorology* 151, 139–178.

Krayenhoff ES, Santiago J, Martilli A, Christen A, Oke TR, 2015: Parametrization of drag and turbulence for urban neighbourhoods with trees. *Boundary-Layer Meteorology* 156, 157–189.

Krupnick AJ, Harrington W, Ostro B, 1990: Ambient ozone and acute health effects: Evidence from daily data. *Journal of Environmental Economics and Management* 18, 1–18. DOI: 10.1016/0095-0696(90)90048-4

Kusaka H, Kondo H, Kikegawa Y, Kimura F, 2001: A simple single-layer urban canopy model for atmospheric model: comparison with multi-layer and slab models. *Boundary-Layer Meteorology* 101, 329–358.

Lee S, Park S, 2008: A vegetated urban canopy model for meteorological and environmental modelling. *Boundary-Layer Meteorology* 126, 73–102.

Lippmann M, 1993: Health effects of tropospheric ozone: Review of recent research fundings and their implications for ambient air quality standards. *Journal of Exposure Analysis and Environmental Epidemiology* 3, 103–129.

Louis JF, 1979: A parametric model of vertical eddy fluxes in the atmosphere. *Boundary-Layer Meteorology* 17, 187–202. DOI: 10.1007/BF00117978

McPherson G, Simpson JR, Peper PJ, Maco SE, Xiao Q, 2005:
Municipal forest benefits and costs in five US cities. *Journal of Forestry* 103, 411–416.

Ministry of Internal Affairs and Communications (MIAC), 2005: *The National Census of Japan*. Available online: http://o-stat.go.jp/S2G2/esStatGIS/page/download.html

Ministry of Land Infrastructure Transport and Tourism (MLIT), 2006: *Digital National Land Information*. Available online: nlftp.mlit.go.jp/ksj/

Nakanishi M, Niino H, 2006: An improved Mellor–Yamada level-3 model: its numerical stability and application to a regional prediction of advection fog. *Boundary-Layer Meteorology* 119, 397–407. DOI: 10.1007/s10546-005-9030-8

Onishi A, Cao X, Ito T, Shi F, Imura H, 2010: Evaluating the potential for urban heat-island mitigation by greening parking lots. *Urban Forestry and Urban Greening* 9, 323–332. DOI: 10.1016/j.ufug.2010.06.002

Peng S, Piao S, Ciais P, Friedlingstein P, Otle C, Breon F, Nan L, Zhou L, Myneni RB, 2012: Surface urban heat island across 419 global big cities. *Environmental Science and Technology* 46, 696–703. DOI: 10.1021/es2030438

Rosenfeld AH, Akbari H, Romm JJ, Pomerantz M, 1998: Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings* 28, 51–62. DOI: 10.1016/S0378-7788(97)00063-7

Ryu Y, Bou-Zeid E, Wang Z, Smith J, 2016: Realistic representation of trees in an urban canopy model. *Boundary-Layer Meteorology* 159, 193–220.

Saitama Pref., 2017: 2nd Green Plan in Saitama (in Japanese). Available online: https://www.pref.saitama.lg.jp/a0508/documents/00_zenpen.pdf

Saito K, Fujita T, Yamada Y, Ishida J, Kumagai Y, Aranami K, Ohmori S, Nagasawa R, Kumagai S, 2006: The operational JMA nonhydrostatic mesoscale model. *Monthly Weather Review* 134, 1266–1298. DOI: 10.1175/MWR3120.1

Sakurai M, Shinohara Y, Mashimo K, Sunaga T, 2009: High temperature in summer of 2007 when the daily maximum temperature is over 40 °C in Kanto area: Part 1 Case study of 15 and 16 August 2007 (in Japanese). *TENKI* 56, 248–253.

Salbitano F, Borelli S, Conigliaro M, Chen Y, 2016: *Guidelines on Urban and Peri-urban Forestry*. Rome: Food and Agriculture Organization of the United Nations.

Santamouris M, 2014: Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environment. *Solar Energy* 103, 682–703.

Sato Y, Higuchi A, Takami A, Murakami A, Masutomi Y, Tsuchiya K, Goto D, Nakajima T, 2016: Regional variability in the impacts of future land use on summertime temperatures in Kanto region, the Japanese megacity. *Urban Forestry and Urban Greening* 20, 43–55. DOI: 10.1016/j.ufug.2016.07.012

Scherer D, Fehrenbach U, Beha H, Parlow E, 1999: Improved concepts and methods in analysis and evaluation of the urban climate for optimizing urban planning processes. *Atmospheric Environment* 33, 4185–4193. DOI: 10.1016/S1352-2310(99)00161-2

Stock TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, (Eds.), 2013: *Climate Change 2013: The Physical Science Basis*. IPCC. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1535.

Stone B, 2007: Urban and rural temperature trends in proximity to large US cities: 1951–2000. *International Journal of Climatology* 27, 1801–1807. DOI: 10.1002/joc.1555

Takebayashi H, Moriyama M, 2012: Study on surface heat budget of various pavements for urban heat island mitigation. *Advances in Materials Science and Engineering* 2012, 1–11. DOI: 10.1155/2012/523051

Tong H, Walton A, Sang J, Johnny C, 2005: Numerical simulation of the urban boundary layer over the complex terrain of Hong Kong. *Atmospheric Environment* 39, 3549–3563. DOI: 10.1016/j.atmosenv.2005.02.045

TreePeople, 2016: Available online: https://www.treepeople.org

United Nations, 2014: *World Urbanization Prospects: The 2014 Revision*. New York, United Nations. DOI: 10.4054/DemRes.2005.12.9

U.S. Geological Survey (USGS), 1996: *Global 30 Arc-Second Elevation (ETOPO3)*. Available online: https://lta.cr.usgs.gov/ETOPO3

Yamada Y, 2003: Cloud microphysics (in Japanese). *JMA Numerical Prediction Division Report* 49, 52–76.

Yoshida S, Ooka R, Murakami S, Harayama K, 2002: Effects of artificial heat release on heat island phenomena in Tokyo area using CFD analysis. *Monthly Journal of the Institute of Industrial Science* 54, 79–93.

Yu C, Hien WN, 2006: Thermal benefits of city parks. *Energy and Buildings* 38, 105–120. DOI: 10.1016/j.enbuild.2005.04.003

Zhou L, Dickinson RE, Tian Y, Fang J, Li Q, Kaufmann RK, Tucker CJ, Myneni R, 2004: Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences of the United States of America* 101, 9540–9544. DOI: 10.1073/pnas.0400357101