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# Evaluation of the impact of the urban heat island on residential and commercial energy consumption in Tokyo

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ABSTRACT

This study evaluated the impact of the urban heat island (UHI) in the Tokyo metropolitan area on energy consumption in the residential and commercial sectors. Although there are many indications that UHIs increase energy consumption by air conditioners, the possible decrease in consumption of heating energy in winter is usually ignored. To quantify the net impact of a UHI, it is crucial to consider both factors. Furthermore, it is important to consider the spatial distribution because a UHI represents the local temperature change in an urban area, and the spatial distribution of energy consumption in an urban area is complicated. We developed a new method to evaluate UHI impact by taking into consideration the spatial and temporal distributions of both energy consumption and air temperature. The results reveal that the UHI increases commercial energy consumption in the Tokyo metropolitan area but decreases residential energy consumption; however, there is a total net decrease in energy consumption. This suggests that UHI mitigation measures should particularly target the city center, where commercial buildings are concentrated, whereas in residential areas, sufficient assessments must be conducted to ensure that mitigation measures are introduced with caution.



## 1. Introduction

Urbanization has various impacts on urban environments. One of the more serious impacts of urbanization is the rise in temperature due to artificial land cover and anthropogenic heat, i.e., urban heat islands (UHIs). UHIs are an important issue for urban planning and environmental control because there are many indications that UHIs have several negative impacts on an urban environment.

Numerous studies have reported a conspicuous UHI in the Tokyo metropolitan area [1–7]. For a long time, the main objective of many studies conducted on UHIs was to understand the actual conditions and mechanism of the phenomenon. In recent years, sufficient knowledge of UHIs has accumulated, and the next step is to alleviate their negative impacts. In Japan, the Ministry of the Environment and various local governments have instituted measures to mitigate UHIs [8]. However, because the social and economic impacts of UHIs are not necessarily well defined, it is difficult to evaluate the effects of those mitigation measures.

In particular, increased energy consumption by air conditioners is frequently identified as a serious impact of UHIs [2,9–11]. It is extremely important to consider this impact because energy saving is intimately connected with countermeasures against global warming. In fact, many evaluations have already been conducted on the energy-saving effects of UHI mitigation measures, such as high-albedo coatings and urban greening in many cities in the United States and Canada [12–20]. However, in the Tokyo metropolitan area, although there are many qualitative indications that the UHI increases energy consumption for cooling in summer (e.g., [2,21]), quantitative verifications are still lacking. A few quantitative evaluations of the energy-saving effects of UHI mitigation have been conducted [22–25], but the target areas and weather conditions in these studies have been limited. Furthermore, these studies evaluated only the effects on cooling-energy consumption in summer, even though UHI mitigation may increase heating-energy consumption in winter. Ihara et al. [26] simulated the year-round air temperature and annual energy consumption in an office district in Tokyo and quantified effects of UHI countermeasures on both cooling- and heating-energy consumption. In addition, Ihara et al. [27] analyzed electricity consumption in actual office buildings and derived the sensitivity of electricity consumption to air temperature and humidity to evaluate the effect of the UHI. Nevertheless, the target area and building types were still limited in those studies [26,27].

Akbari and Konopacki [18] conducted a practical study that estimated the energy-saving potential of several UHI mitigation

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measures in Toronto. Their results indicated that the energy-saving effects vary depending on the mitigation measures and building types. However, that study did not consider the temperature distribution in the urban area. Akbari [28] and Akbari et al. [29] also conducted practical measurement and simulation studies, respectively, to demonstrate the energy-saving effects of high-albedo coatings. However, those studies did not explicitly evaluate the effect of the decrease in ambient air temperature.

To save energy by UHI mitigation, it is crucial to select appropriate mitigation measures that are suitable for each area. To this end, an important point that must be considered is seasonal variation. In an area where the influence of a UHI is stronger in winter than in summer, a mitigation measure that decreases the temperature throughout the year may cause an increase in energy consumption. In such an area, a mitigation measure that is effective in summer should be given priority (e.g., urban greening using deciduous trees). Another important point that must be considered is the spatial distribution of the area. A UHI is a phenomenon of local temperature change, and its shape, location, and intensity vary depending on the time and season. Furthermore, the spatial distribution of energy consumption in urban areas is complicated. Therefore, to select appropriate mitigation measures, it is necessary to evaluate the impact in detail to understand the spatial and temporal distributions of both the UHI and energy consumption.

Impact evaluations of UHIs on energy consumption have already been conducted in several cities, such as Athens [30–32], London [33,34], and Taipei [35]. However, the number of studies is still insufficient because the effects depend on a variety of factors such as climatic conditions, thermal performances of buildings, lifestyles, and so on. Hence, it is necessary to conduct similar evaluations in many cities of the world. Shimoda et al. [36] established a detailed model to simulate residential energy consumption in Osaka City, Japan. The model, which is applicable to evaluations of UHI impacts, expresses various behaviors of inhabitants and calculates the air-conditioning load in the whole Osaka City area. However, their study did not address the impact of actual temperature increase due to the UHI. In addition, most of the aforementioned existing studies were conducted based on air-conditioning load calculations, which require many input parameters (e.g., the heat insulation of walls, the type of air-conditioning system, area ratio of windows on walls, and so on). The results of such calculations strongly depend on the parameter values used, but it is difficult to set precise parameter values because cities include a wide variety of building types, and surveys of current conditions of existing buildings are often lacking. Therefore, an alternative method that is widely applicable to cities is required.

Large-scale energy-evaluation studies have investigated the temperature sensitivity of energy consumption to predict energy demand and evaluate climatic conditions (e.g., [37–39]). However, these studies derived temperature sensitivity from supply-side data, from which it is difficult to consider detailed temperature distributions in an urban area and thus to evaluate the impact of the UHI. Using supply-side data, Fung et al. [40] evaluated the impact of temperature increase due to urban effects on energy consumption. Although they estimated the temperature sensitivity of energy consumption in Hong Kong, they did not account for the spatial and temporal distributions of urban temperatures.

Against this backdrop, the objective of this study was to quantify the effects of the UHI in the Tokyo metropolitan area on local energy consumption by taking into consideration the spatial and temporal distributions of both energy consumption and air temperature. To achieve this, we developed a new method using a meteorological model and specific energy consumption data. Many numerical studies of UHIs have been conducted using meteorological models. In this study, we focused not on the meteorological simulation itself but on the evaluation of energy consumption based on the meteorological simulation results. Specifically, we focused on primary energy consumption for space cooling, space heating, and water heating in the commercial and residential sectors. Fig. 1 shows the study area. Incidentally, it should be noted that this evaluation was a case study of Tokyo. Although the evaluation method proposed in this paper appears to be general purpose, the results are applicable only to the Tokyo metropolitan area.

## 2. Methodology

Many studies have been conducted on energy consumption with respect to air temperature sensitivity [37–48]. This knowledge is useful for predicting energy demands under various weather conditions, such as hot summers and cool summers. Many evaluations of the impact of global warming on energy consumption have also been conducted using this approach. However, in these studies, the relationship between energy consumption data from the supply side (e.g., electric power plants or city gas supply companies) and the average temperature of the supply area was analyzed; therefore, spatial distribution was not considered. This approach is insufficient for assessing the impacts of UHIs, which represent local temperature changes in urban areas.

On the other hand, numerous studies have been conducted on the spatial distribution of energy consumption [6,49–52]. In these studies, spatial data based on the floor area or the number of households were multiplied by the specific energy consumption. Specific energy consumption is defined as the energy consumption per standard unit of floor area or the number of households. However, this method is also not suitable for evaluating the impact of an UHI because it cannot consider the influence of temperature.

Therefore, we evaluated the impact of an UHI on energy consumption by considering both temperature sensitivity and spatial distribution, as shown in Fig. 2. The procedure is explained below. First, we established estimation equations by expressing specific energy consumption as a function of temperature. We then calculated the temporal and spatial distributions of temperature using a meteorological model. This calculation was performed for two cases: the first was the present case, which was performed under the present conditions, and the second was the no-UHI case,

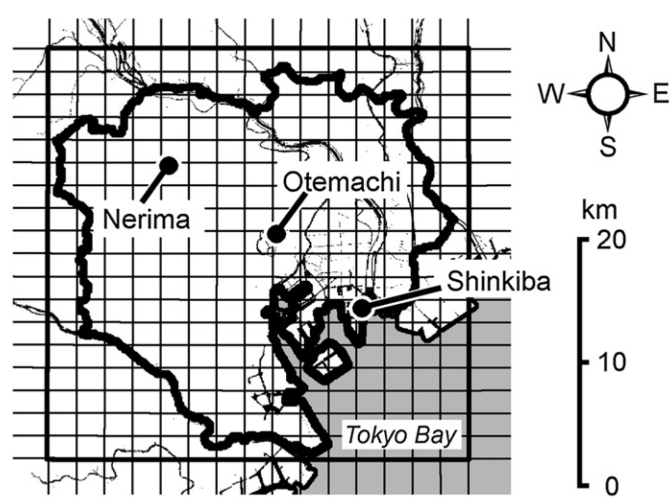


**Fig. 1.** Study area and computational grid for the meteorological model. The thick line delineates the area of Tokyo's 23 wards for which energy consumption was calculated in this study. Solid circles mark the observation points of the Automated Meteorological Data Acquisition System (AMeDAS).