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Recent Progress on Urban Climate Study in Japan

KUSAKA Hiroyuki

Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8572, Japan

Abstract: A review of urban climate studies in Japan since 1980 is presented. First, we describe recent research on an urban heat island. In this section, we focus on the heat island with a scale larger than a single city, heterogeneous temperature distribution in an urban district, and quantitative analysis of the formation mechanism of the heat island using numerical models. We then summarize the interaction between a sea breeze and a heat island. Cloud formation and precipitation over the urban area are also summarized. Furthermore, recent studies on the estimation of urban surface parameters and anthropogenic heat maps are briefly described. Observational studies on the urban canopy layer are also introduced. Some recent studies on urban planning are introduced, focusing on the cooling effect of parks and rivers on the urban temperature. Finally, we conclude the review by describing ongoing work.

Key words: urban climate, urban heat island phenomenon, sea breeze, convective rainfall, numerical simulation

Introduction

Urbanization alters several interacting atmospheric and surface processes, and, hence, urbanization significantly affects the local climate. As a result, urban climate differs from that of nearby rural areas. Until the 1970s, there were two paths of urban climate study in Japan. One path examined the city-scale heat island phenomenon in order to explain qualitatively its condition and formation mechanism. The other path investigated statistically the long-term trends in temperature, humidity, and rainfall amount. These earlier studies were reviewed by Fukui and Yazawa (1957), Yoshino (1957, 1977), Kawamura (1968, 1977a, b, 1989), and Yamashita (1988, 1990, 1994). However, an understanding of the formation mechanism of the urban climate, the relationship between convective rainfall and a heat island, and the structure of the urban canopy layer was insufficient. Advances in numerical modeling, remote-sensing technique, and measurement equipment have enabled us to overcome these problems and have contributed to the development of urban climate study.

Recently, the focus has changed to (a) the urban heat island phenomenon with a scale larger than a single city, (b) the heterogeneous temperature distribution within an urban district in a city, (c) the quantitative analysis of the formation mechanism of an urban heat island by a numerical model, (d) the interaction between a sea breeze and a heat island, (e) the relationship between convective rainfall and a heat island, (f) the estimation of urban surface parameters and anthropogenic heat, (g) urban planning, (h) observation in and above the urban canopy layer, and (i) the turbulence structure in and above the urban canopy layer. Some of these studies have been recently reviewed by Honjo (2000), Roth (2000), Shepherd (2005), Grimmond (2006), Kanda (2006, 2007), Masson (2006), and Kusaka (2008). In this paper, we provide a review of recent urban climate studies in Japan since 1980. It is noteworthy that, in the present study, fields (f)–(h) are briefly introduced and field (i) is hardly evaluated due to the nature of this journal and space limitations.

Urban Heat Island Phenomenon

Urban heat island phenomenon with the scale of a single city

Surface-layer air in cities is generally warmer than that of its surroundings. Near a city, the pattern of the isotherms on a surface weather

map looks like the topographic contours around an island. Thus, this type of urban warming has become known as the urban heat island phenomenon. Most of the classical studies focused on the most prominent phenomenon, that is, a nocturnal heat island observed in a single city on clear, calm winter days. Observations in this regard are still underway (e.g., Takahashi 1981; Yamashita 1986, 1996; Takahashi and Fukuoka 1994). A characteristic of the recent studies is their focus on summer as well as winter days. Another is to perform multiple observations for a certain city (Sakakibara and Itoh 1998; Sakakibara and Morita 2002) or to utilize the conventional station data (e.g., Kawamura 1985; Fujibe 1993; Mikami et al. 2004; Yamazoe and Ichinose 1994; Yokoyama et al. 2005). Fujibe (1993) described the relationship between the temperature distribution and wind system in spring and summer using the Automated Meteorological Data Acquisition System (AMeDAS) network data with about 20 km spatial resolution for the past 12 years. The Tokyo Metropolitan Research Institute for Environmental Protection established a very high-density observational network called METROS100 that consists of 100 stations for measuring the surface air temperature in central Tokyo. The horizontal resolution of the network is about 2.5 km. METROS100 can show the detailed temperature distribution in Tokyo, which is not fully confirmed by the AMeDAS network data operated by the Japan Meteorological Agency. Another characteristic of recent research is to utilize remote-sensing techniques to estimate surface skin temperature from aircraft (e.g., Hoyano et al. 1981, 1994; Iino and Hoyano 1996; Sugawara et al. 2001) and satellite (e.g., Kondo et al. 1993).

Climatologists have tried to determine the time of day when the heat island phenomenon appears most clearly as well as the temperature distribution. Sakakibara and Morita (2002) recently reported that the best time to observe the heat island phenomenon is several hours after sunset using automobile measurement for 83 days in Hakuba (a small town). The same conclusion was reached after a statistical analysis of data at stations in the medium-sized city of Kumamoto (Tomita et al. 2007) and metropolitan Tokyo (Yamazoe and Ichinose 1994).

Urban heat island phenomenon with a scale larger than a single city

An urban heat island with a scale larger than a single city has also received attention (Fujibe 1993, 1994, 1996; Kusaka et al. 2000). Figure 1 illustrates how the daily maximum temperature in summer tends to increase in the inland area

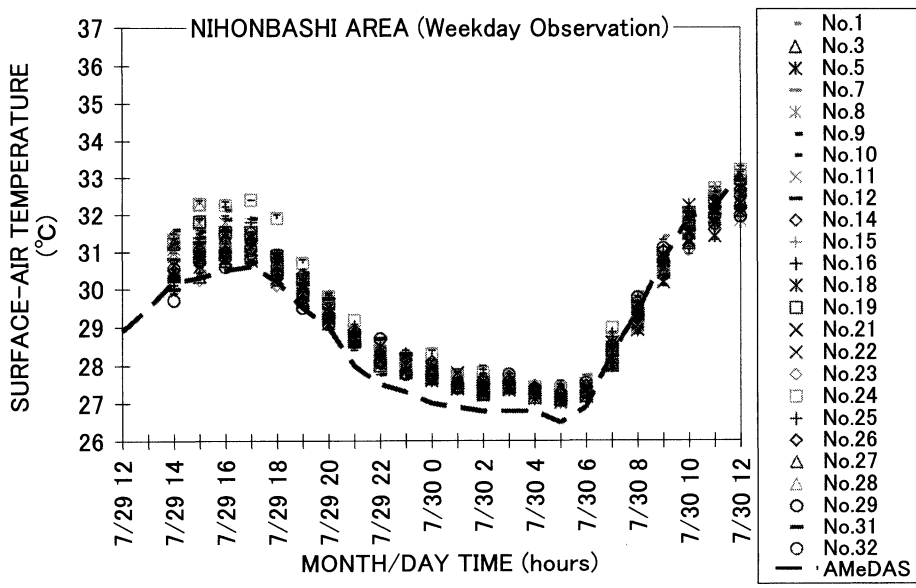


Figure 1. Diurnal variation of surface air temperature observed within urban canopy layer in Nihonbashi area (Symbols) and over the open space in Otemachi area (Dashed line). (Ohashi et al. 2007).

of the Kanto plain as well as around Tokyo. Kusaka et al. (2000) conducted numerical experiments to estimate the impact of land-use alteration on the daytime heat island on a clear, calm summer day. From the experiments, it was confirmed that warming due to land-use alterations in the past 85 years is clearly observed in northern metropolitan Tokyo. Furthermore, they showed the warming results from the enhanced sensible heat flux and the change in the interaction between the boundary layer heating and the sea breeze front.

Spatial distribution of the surface air temperature in an urban district

Recent concern about the urban temperature has been shifting to heterogeneous horizontal spatial distribution in an urban district (a city block) (e.g., Sugawara et al. 2004a, 2006; Ohashi et al. 2007). Ohashi et al. (2007) observed the surface air temperature at 27 points per 50,000 m^2 in the Nihonbashi district (an office area) in Tokyo. They found that the temperatures between buildings were generally higher than the temperature above the open space at nighttime (Fig. 2). This indicates that the urban canopy structure plays a significant role in the nocturnal heat island phenomenon. Another interesting result is that the surface air temperature takes a heterogeneous distribution in the daytime, whereas it becomes homogeneous after sunset on a clear, calm summer day. Kanda et al. (2006) measured the temperature profiles in the urban roughness layer at the five towers located at the Kugahara residential area in Tokyo and confirmed that the difference in the profile between towers was quite small at night but became relatively large in the morning when each tower was built at 200 m intervals. These reports indicate that the heat island intensity is sensitive to the location of the observation site. Sugawara et al. (2004a) proposed a method to estimate an area-averaged air temperature over the heterogeneous surface that is based on the hydrostatic equation and the vertical pressure gradient.

Formation mechanism of the urban heat island phenomenon

Previous observational and analytical studies have proposed several hypotheses to explain the formation mechanism of this phenomenon as well as several factors affecting it. The proposed factors are (i) anthropogenic heat release, (ii) enhanced mechanical turbulence, (iii) decreased moisture availability and enhanced sensible heat flux, (iv) enhanced thermal inertia, (v) decreased surface albedo, (vi) decreased sky view factor resulting in reduced radiation cooling, and (vii) decreased wind speed resulting in weak ventilation. Many researchers have attempted to statistically relate the magnitude of the heat island intensity to the anthropogenic heat and surface parameters (e.g., Takahashi 1981; Fukuoka 1983; Yamashita 1986; Sakakibara and Itoh 1998; Yamada and Maruta 1989). Fukuoka (1983) reported that the heat island intensity is related to the population in the city but the coefficient is larger in big cities than in small cities. He speculated that the enhanced anthropogenic heat release was responsible for these differences. However, further research was needed because individual factors bring about

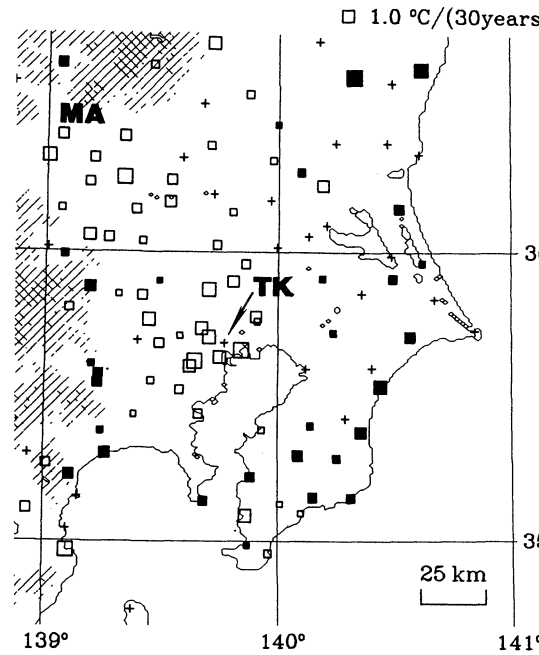


Figure 2. Distribution of the daily maximum temperature warming rate for 1946–1976.

Open and closed squares indicate positive and negative values respectively, with their areas proportional to their absolute values (Fujibe 1994).

the problem of multicollinearity in the statistics.

Fujibe (1987) estimated the impact of the anthropogenic heat on the urban temperature using an interesting approach whereby the difference in the temperature between weekdays and weekends is calculated. On the other hand, field experiments in Tsukuba (a small town) (Tamiya and Oyama 1981) and Sapporo (a large city) (Uno et al. 1988) showed the importance of the enhanced mechanical turbulence. Tamiya and Oyama (1981) and Uno et al. (1988) observed that the difference between column heats above urban and rural sites is much larger than the difference of the anthropogenic heat during the nighttime on a windy winter day. Furthermore, Uno et al. (1988) found that the maximum downward transport of the sensible heat appeared around the top level of the heat island. Numerical experiments using a simple multi-layer urban canopy model supported the conclusion (Uno et al. 1989). Sakakibara (2001) also came to a similar conclusion for the heat island of Obuse (a small town).

Another approach to confirm the individual causations is numerical experiments. Kimura and Takahashi (1991) examined the main factor of the heat island of Tokyo on a clear, calm summer day using a numerical model specially improved for urban climate simulations. The results demonstrated that the intensity of the daytime and nighttime heat island was mostly the result of the small latent heat release and large anthropogenic heat release from the urban surface, respectively (Fig. 3). However, a clear explanation for factors (vi) and (vii) was not offered because of the lack of urban canopy effects in their model.

Recently, in order to overcome the problem, Kondo and Liu (1998) and Kondo et al. (2005) developed a multi-layer urban canopy model, Kusaka et al. (2001) developed a single urban canopy model, and Kikegawa et al. (2003) developed a building energy model. Kusaka and Kimura (2004a) confirmed that the atmospheric model coupled with the canopy model accurately simulated the linear drop in surface air temperature after sunset that is well known as a feature of urban temperature. Kusaka and Kimura (2004b), using the coupled model, showed that the anthropogenic heat release and enhanced heat capacity increased the urban temperature in the early morning, whereas the reduced sky view factor increased the temperature for several

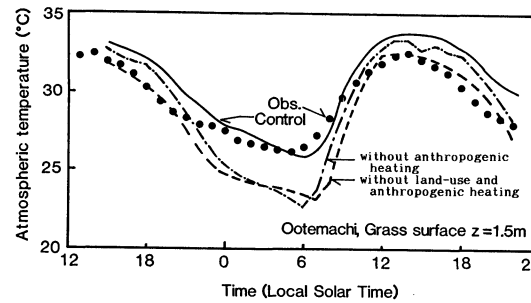


Figure 3. Diurnal variation of surface air temperatures from the observation and numerical experiments.

Closed circle indicates observed temperature. Solid line indicates the temperature from the control experiment. Dashed-dotted line indicates the result from the experiment without anthropogenic heating. Broken line indicates the result from the experiment without land-use and anthropogenic heating (Kimura and Takahashi 1991).

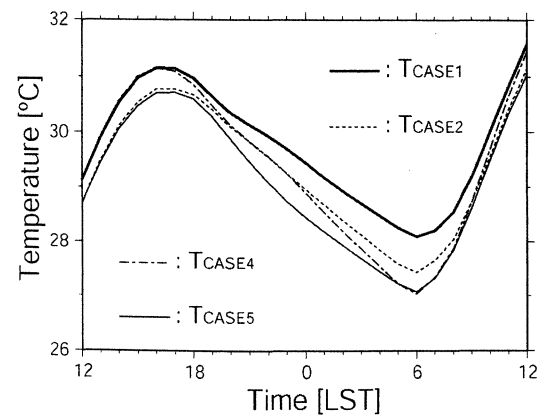


Figure 4. Diurnal variation of surface air temperature from the sensitivity experiments.

The thick solid line is from Case 1, the dashed line is from Case 2, the dashed-dotted line is from Case 4, and the thin solid line is from Case 5. Case 1 is control experiment. Case 2 was run with the same parameters as Case 1, except with no anthropogenic heating. Case 4 was run with the same parameters as Case 2, except that the heat capacity is 60% of Case 2. Case 5 was run with the same parameters as Case 2, except that the urban walls do not contribute to radiations (Kusaka and Kimura 2004b).

hours after sunset on a clear, calm summer day (Fig. 4). In addition, they confirmed that the impact of the reduced surface albedo was much smaller than that of the others. Tokairin et al. (2006) numerically estimated that the contribution of the reduced ventilation to the formation of the heat island in the Kanda area (an office area) in Tokyo was 41% on a typical clear, calm summer day.

Urban warming and climate change

Recently, it has become important to estimate the long-term change of the heat island intensity from the viewpoint of the global warming. However, for some cities, it is difficult to select appropriate urban and rural sites (e.g., Sakakibara and Owa 2005). Park et al. (1994), Noguchi (1994), Kato (1996), and Kusaka et al. (1998) attempted to overcome the problem using a statistical approach. Similar work should be continued in the future.

On the other hand, the relationship between a heat island and an extremely hot day has been reported by Fujibe (1994, 1998a). Fujibe (1998a) showed that extremely hot days (with a maximum temperature over 36 degrees C) tend to increase in the inland area of the Kanto plain and speculated that the increase may be caused by the urban effect.

Wind System

The urban heat island theoretically causes local wind circulations analogous to sea breeze circulation. This flow is called heat island circulation. It is noted that the heat island circulation can develop more strongly in the daytime rather than at nighttime because the urban-rural pressure difference and vertical mixing in the daytime are larger than those at nighttime. However, there have been few field measurements of the circulation, in part because of the difficulty of separating the components of the wind circulation. In fact, the enhanced wind speed toward the city due to the urban heat island was about $0.2\,\mathrm{m\,s^{-1}}$, which was an anomaly from values horizontally averaged in the area (Fujibe and Asai 1980).

Recently, the interaction between the urban heat island and sea breeze circulation has been a focus of attention because most large urban areas are located in the coastal region in Japan. Yoshikado and Kondo (1989) observed that a sea breeze front was formed over the Tokyo metropolitan area and its advance was much slower over the urban area than over the inland rural area due to the daytime heat island effect. Yoshikado (1992, 1994) confirmed the results of Yoshikado and Kondo (1989) using a two-dimensional atmospheric model. Kusaka et al. (2000) conducted simulations using land-use data for 1900, 1950, and 1985 and showed that the simulated sea breeze front is more clearly defined around the northern end of the Tokyo metropolitan area and requires more time to reach the inland area due to land-use alterations in the past 85 years (Fig. 5). The local wind circulation achieves a more complex flow when there are two large cities in the same area, such as Osaka and Kyoto. Ohashi and Kida (2002a, b, 2004) carried out a numerical simulation for this area and found that a "chain flow" develops there, where the chain flow is defined as the flow downward from the upper layer over the coastal urban area to the lower layer over the inland urban area.

Cloud Formation and Convective Rainfall

The relative humidity is generally lower in urban areas than in rural areas. However, the difference in the relative humidity between urban and rural areas has shown a tendency to decrease in the last 20 years (Omoto et al. 1994). The difference in the water vapor pressure has also become smaller. From these results, Omoto et al. (1994) and Fujibe (2002) suggested that anthropogenic latent heat has been recently released from urban areas. Kanda et al. (1997) supported their conclusions from the results of a field experiment to measure the latent and sensible heat fluxes using the scintillation method. Anthropogenic latent heat is currently the focus of attention because people feel more uncomfortable as the humidity increases (e.g., Yamada 2007) and this could result in the formation of low clouds (Fujibe 2002).

It is considered that the urban heat island affects cloud formation. Kai et al. (1995) studied

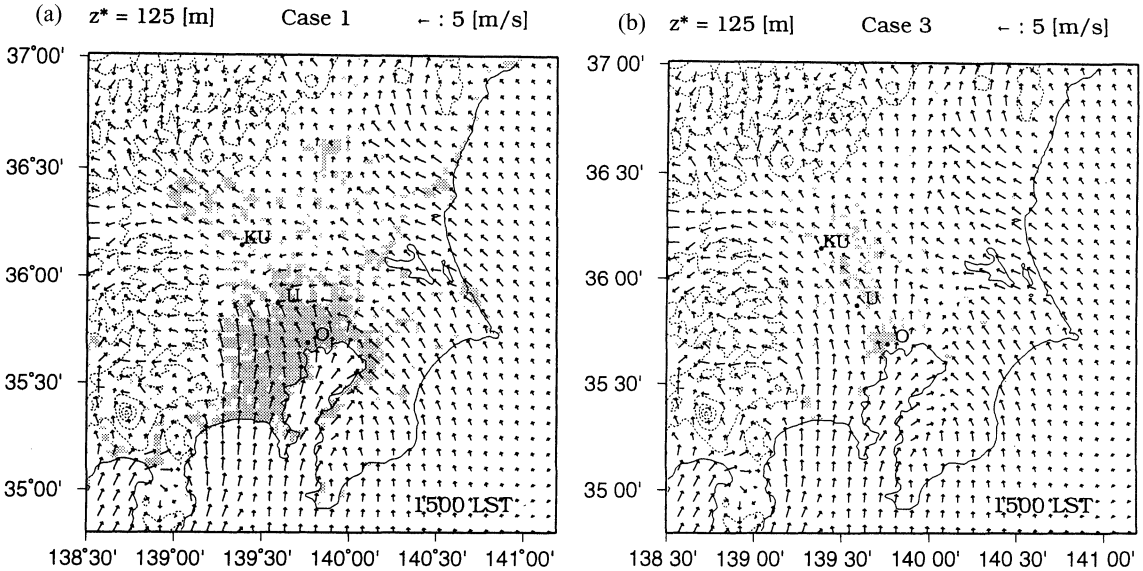
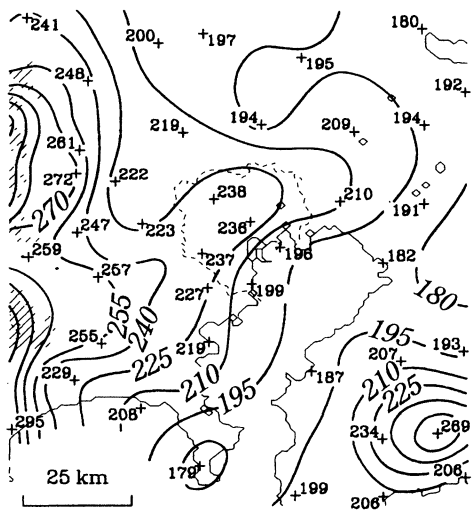


Figure 5. Wind system at 1500 Local Solar Time from the numerical simulations, using the land use for 1985 and 1900 respectively.

The shaded areas indicate the urban areas. The symbol of KU, U, and O means Kumagaya, Urawa (Saitama), and Otemachi (Tokyo), respectively. (Kusaka et al. 2000).

a low-level cumulus cloud line called the "Kanpachi Street Cloud," which is approximately 500 m wide and several tens of kilometers in length and is frequently observed over a major road, "Kanpachi Street," in Tokyo. They speculated that important factors for the formation of the cloud line were the moist air convergence of the sea breezes and the urban heat island of Tokyo. Yamada (1999) and Kanda et al.(2001) confirmed their expectations using numerical experiments. Inoue and Kimura (2004) made a composite cloud image over the Tokyo metropolitan area using satellite data of the past eleven years and found that some cloud lines frequently appear over the urban areas that are not covered by the sea breezes.

Changes in the precipitation pattern and long-term trend in and around urban areas have been of general interest since Changon (1968). A large project, METROMEX, confirmed that the precipitation is enhanced in and downwind of St. Louis, MO, USA (Changon 1981). Yonetani (1982) reported that the number of heavy rainfall days in August increased in the Tokyo metropolitan area in the 1954–1976 period. Sato and Takahashi (2000) confirmed a similar result for the 1976–1998 period. However, there is no evidence for the months of July and September. Fujibe (1998b) investigated the spatial distribution of precipitation in and around Tokyo using the data of the raingauge network for the past 16 years (1979–1994) and found a positive anomaly of the precipitation in Tokyo in the afternoons in the warm season (Fig. 6). Furthermore, it was confirmed that the anomaly tended to be enhanced in the early afternoon in the warm season, particularly regarding heavy rainfall. Sato et al. (2006) conducted a lag composite analysis of the precipitation frequency for 71 clear calm summer days. As a result, they found that the precipitation frequency in Tokyo was remarkably higher than that in the surrounding areas. Fujibe et al. (2002) and Fujibe (2003) statistically showed that the typical wind pattern before the short-time heavy rainfall in Tokyo under synoptic conditions in a calm summer is the "E–S type," in which easterly winds from the east coast and southerly winds from the south coast of the Kanto plain converged in Tokyo. Nakanishi and Hara (2003) and Sawada and Takahashi (2007) came to a similar conclusion from their case study and statistical analysis, respectively. Numerical studies also showed that urbanization enhanced the wind convergence over the Tokyo



Precipitation (Apr.– Sep., 12– 18 JST)

Figure 6. Distribution of precipitation amount (mm) in and around Tokyo for 1200–1800 Japan Standard Time during the warm season (April–September).

Dotted line indicates the boundary of the central part of Tokyo (Fujibe 1998b).

metropolitan area (e.g., Kusaka et al. 2000; Kanda et al. 2001). However, definite results have not been obtained from realistic simulation of the convective rainfall in Japan. It is believed that a simple sensitivity experiment based on determinism is not suitable for this problem because the terrain effect can conceal the urban one and the simulation of the convective rainfall easily becomes chaotic.

Some results from long-term historical data cast doubt on the impact of the heat island on the convective rainfall, such as the contribution of the heavy rainfall amount to the total rainfall amount (Takahashi 2003), and the number of heavy rainfall events (Kanae et al. 2004) in Tokyo has decadal scale variability and increased until the 1940s and after the 1980s. These findings indicate that the conclusion is strongly dependent on the periods used in the analysis. Kanae et al. (2004) pointed out that heavy rainfall over an urban area strongly depends on large-scale climate change, which results from comparing the frequency of urban heavy rainfall and a synoptic scale phenomenon, such as a tropical cyclone or the Baiu front. From these findings, we can understand that it is currently very hard to draw a conclusion and, hence, further research is needed.

Surface Parameters and Anthropogenic Heat

Surface parameters, such as the albedo and roughness length, are important to understand the difference in the surface heat budget between urban and rural areas. Aida (1982) estimated the surface albedo for several types of urban canopy using a scale model experiment. Aida and Gotoh (1982) numerically estimated the surface albedo. Nakagawa (1996) and Kanda et al. (2005a) developed simple theoretical radiation schemes for regular building arrays. Remote-sensing techniques are widely used today to estimate the surface albedo (e.g., Takamura 1992; Nakagawa and Nakayama 1995), thermal inertia (e.g., Sugawara et al. 2001), and vegetation cover ratio (e.g., Honjo and Takakura, 1987, 1989; Hirano et al. 2002). Another new tool, the Geographic Information System (GIS), is also used to estimate the roof area (e.g., Izumi and Matsuyama 2004). On the other hand, Moriwaki and Kanda (2006) estimated the ratio of the roughness length of the momentum to heat using data measured at the 29 m tower located at the Kugahara residential area. Kanda et al. (2007) estimated the roughness lengths for the momentum and heat from the outdoor urban scale model experiments.

Estimating anthropogenic heat has recently become an interesting field. Kimura and Takahashi (1991) made an anthropogenic heat map using the unit value method and added it to the atmospheric model. Ichinose et al. (1999) made a more detailed anthropogenic heat map with 500 m horizontal resolution. In their studies, the anthropogenic heat has a diurnal variation but is statically added to the atmospheric model. Recently, Kikegawa et al. (2003) developed a building energy model to estimate the anthropogenic heat depending on the atmospheric condition. Such a model permits conducting a heat island simulation considering the interaction between the temperature and anthropogenic heating. Ohashi et al. (2007) estimated the anthropogenic heat from air-conditioners increases the daytime

temperature by 1–2 degrees C, using the coupled system of the atmospheric model, canopy model, and building energy model.

Urban Planning

In Germany, "Klimaatlas" (Climate Atlas) is used for urban planning. Along these lines, Moriyama and Takebayashi (1999) attempted to make a Klimatope map for the Klimaatlas of Kobe city, and their research group then started putting together a Klimaatlas of all major Japanese cities (Architectural Institute of Japan 2000). Geographers have recently been interested in urban planning, particularly in the effect of parks on heat islands. The wind ventilation lane maintained by a river has also been a topic of interest. Thus, recent studies in this field are briefly reviewed in the present paper.

Parks in a city are cooler than their surroundings (e.g., Yamada and Maruta 1989; Hamada and Mikami 1994). As a result, parks form a cool island in a city. Researchers have been investigating the temperature distribution in and around parks. It is reasonable that a park in a city reduces the temperature of its leeward areas due to cold air advection (e.g., Honjo et al. 1998, 2000). On the other hand, it has been pointed out that large parks reduce nocturnal temperature near the park even on calm nights. Narita et al. (2004) recently observed the very weak cold outflow of 0.1–0.3 m/s from the Shinjuku-Gyoen Park, located in the commercial area of Tokyo, using automatic temperature recorders and three-dimensional ultrasonic anemometer-thermometers. In addition, they confirmed that its influence reaches constructed areas 80–90 m away from the park.

Recently, roof-top greening has become an issue of interest. Indeed, it produces very weak drainage flow from the roof, but its effect on the urban temperature could work for only a limited area around the building (e.g., Hagishima et al. 2004). Numerical experiments have indicated that roof-top greening has a relatively small impact on the surface air temperature (e.g., Hagishima et al. 2002), whereas greening at the ground level reduces the temperature slightly more (e.g., Yoshida et al. 2000).

Rivers in a city are also expected to decrease the temperature of their surroundings. Murakawa et al. (1990) found that the cooling effect of a river with a width of 260 m reaches 400 m away from it when sea breezes blow along the river. On the other hand, it is speculated that rivers lead the cold air mass to the inland urban area (Katayama et al. 1990; Hashimoto et al. 2001). Narita (1992) conducted wind tunnel experiments and determined that the location and direction of building distribution to wind direction are as important as the building density around the river. Numerical experiments using a CFD model showed that construction of high buildings in the waterfront area of Tokyo (Shiodome area) reduced the sea breezes and increased the temperature in the leeward areas, which also indicates the importance of building distribution in mitigating the heat island phenomenon (Ashie and Kono 2006).

Nocturnal drainage winds blowing along the valley also reduce the heat island. Kanou and Mikami (2003) observed that a high-temperature area appears in the urban area located at the entrance to the valley in the daytime but in the leeward area after sunset.

Urban Canopy Layer

Observations in and above the urban canopy layer have also been a focus of attention (e.g., Nakamura and Oke 1988; Yoshida et al. 1990/1991; Sakaida and Suzuki 1994; Takahashi and Fukuoka 1994; Kanda et al. 1997, 2002, 2005b, 2006; Moriwaki and Kanda 2006; Moriwaki et al. 2006). A characteristic of recent studies is that they included field experiment in some projects, which enabled us to conduct measurements at towers. Kanda et al. (1997) and Kanda et al. (2002) performed field experiments using eddy correlation and scintillation methods to investigate the sensible and latent heat fluxes from the urban canopy layer at the tower built in the Ginza commercial area and the Setagaya residential area of Tokyo, respectively. As a result, Kanda et al. (1997) found that the latent heat flux is comparable to the sensible heat flux in summer because of the artificial latent heat release from the cooling systems of office buildings. In addition, Kanda et al. (2002) proposed a new non-dimensional shear function that is

suitable for the urban area. Kanda et al. (2005b) measured the temperature profile at the 29 m tower built in the Kugahara residential area and found that the daily maximum temperature was observed at the roof level in winter but near the ground in summer.

On the other hand, Jeong et al. (1997) measured how radiation affects the human body in the urban street canyon, and Yamada (2007) numerically estimates the effect of gas radiation on radiative heat transfer between human body and urban street canyon.

Concluding Remarks

Recent progress on urban climate study in Japan was reviewed, focusing on recent concerns, as follows.

(1) Urban heat island with a scale larger than a single city

(2) Heterogeneous temperature distribution in the urban district

(3) Quantitative analysis of the formation mechanism of the heat island using the numerical model

(4) Interaction between a sea breeze and the heat island

(5) Urban effect on the cloud formation and convective rainfall

(6) Estimation of the urban surface parameter and anthropogenic heat map

(7) Observational studies on the urban canopy layer

(8) Urban planning, focusing on the cooling effect of parks and rivers

Japanese scientists have contributed to the urban climate field. Recent contributions are particularly important. Indeed, Japanese participants in the last three International Conferences on Urban Climatolology (ICUC) made up 10–30% of the total number of attendants (Ichinose 1997; Mori et al. 2001; Sugawara et al. 2004b), and they were the largest percentage of attendees at the last two conferences. Recent large projects involving the field experiments BUBBLE and ESCOMPTE have certainly contributed to the advance of urban climate study. Projects involving field experiments (e.g., Hagishima et al. 2005; Moriwaki et al. 2006) and outdoor scale model experiments COSMO (e.g., Kanda et al. 2007) in Japan are also a significant contribution.

Numerical studies are strong in Japan as well. Recently, the urban canopy model developed in Japan (e.g., Kusaka et al. 2001; Kusaka and Kimura 2004a, b) was officially adopted in the advanced numerical weather prediction model WRF (e.g., Kusaka et al. 2005a, b; Kusaka and Hayami 2006; Skamarock et al. 2005), which is the next-generation model after MM5, having the largest user group in the world. In addition, building-resolving LES and RANS models have been used for urban climate studies in Japan (e.g., Murakami et al. 1999; Kanda et al. 2004; Yamada 2006). Development of software platform for total analysis of urban heat island (Mochida et al. 2000) and comprehensive assessment system on heat island relaxation (Murakami et al. 2006) are also significant research projects, taking advantage of existing technologies. The availability of high-performance super-computers in Japan enables the simulation of the detailed temperature distribution in urban districts (e.g., Ashie and Kono 2006).

The numerical prediction of urban climate is highly required at present due to global warming (e.g., Ministry of Environment 2007). Consequently, a large project including regional and urban climate modeling has started in Japan. Urban climate study is progressing to the next stage.

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