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Urban climate in the Tokyo metropolitan area in Japan

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ABSTRACT

Long-term climate changes related with urbanization in Tokyo, Japan, and recent temperature and heavy rainfall distribution in the Tokyo metropolitan area are reviewed. A relatively high temperature increase in annual mean temperature at the rate of 3.0°C/century was detected in Tokyo for the period 1901–2015. Some observational evidence showed the existence of both thermal and mechanical effects of urbanization on recent heavy rainfall occurrences, and modeling studies also support precipitation enhancement. Urban influences were recognized in other climatological elements, such as number of fog days, relative humidity, and wind circulation.

Introduction

Urban climate and global warming are two major climate changes induced by human activities. The former is more local in nature, and thus needs careful examination based on precise local information. The Tokyo metropolitan area, located in the Kanto Plain in Japan, is one of the largest urbanized areas in the world. Tokyo has developed into a big city over the course of a long history.

Population increase and urban expansion in the Tokyo metropolitan area started in the beginning of the 17th century when Ieyasu Tokugawa set up the central Shogunate at Edo (currently Tokyo) in 1603. After the collapse of the Edo Shogunate in 1868, the Meiji Era started. The city of Edo changed its name to Tokyo, which means eastern capital. The capital city of Japan moved to Tokyo in 1869 from Kyoto, which had been the capital city since 794.

At that point, the Japanese industrial revolution began. The population in Tokyo was approximately 860 thousand in 1872 when the official collection of population statistics started. The population of Tokyo steadily increased to 7.3 million until 1942, when many Japanese cities including Tokyo were burnt out by American bombing during World War II (WWII), drastically decreasing the Tokyo population by 1945 to less than 3.5 million. Part of the observed temperature decrease in Tokyo at that time may have been affected by such reduced urban population and activities (Fig. 1), although more detailed examination is needed to verify this statement. After the end of WWII, rapid population increase continued until the early 1960s, when the population of Tokyo exceeded 10 million. The rate of increase of population in the Tokyo metropolitan area slowed down, with a current population of approximately 11.3 million. On the other hand, the population of the three neighboring prefectures continued to increase until recently, and the total population including these neighboring prefectures exceeded 30 million in the 21st Century (Fig. 1).

Official meteorological observations in Tokyo started in 1875. Since then, the Central Meteorological Observatory

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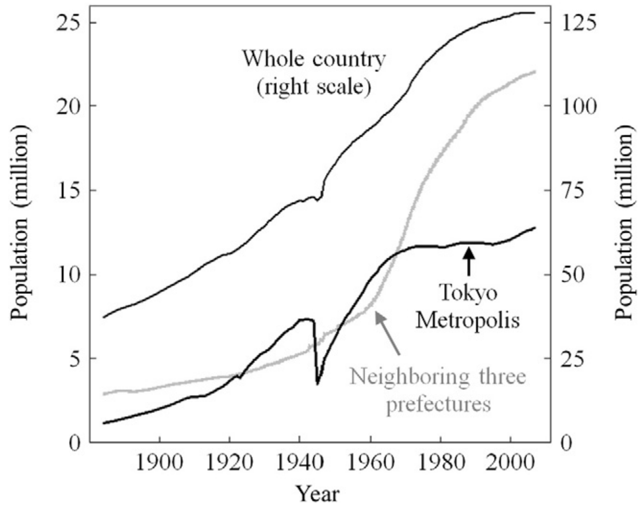

Fig. 1 – Long-term changes of population of Tokyo Metropolis and three neighboring prefectures (Saitama, Chiba and Kanagawa), as well as population changes in the whole country of Japan (Fujibe, 2011).

(until 1956) and the Japan Meteorological Agency (JMA) continued their observations for more than 140 years, although they moved their observation site three times, in 1882, 1923 and 2014. As early as in the 1920s and 1930s, urban warming has been recognized by observational studies in Japan. For example, Fukui and Wada (1941) presented the temperature distribution during one night on March 1939, showing an approximately 5°C difference between the city center and suburban area (Fig. 2). Extensive research works have been conducted on the urban climate in Japan during the most recent six decades. They are reviewed by Yamashita (1990), Kusaka (2008), and Nakagawa (2011). More recently,

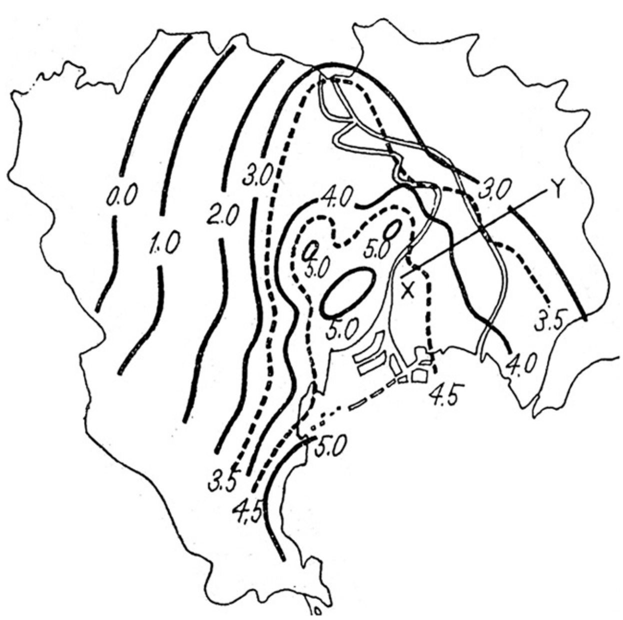

Fig. 2 – Temperature distribution (°C) in Tokyo City (Fukui and Wada, 1941). The observation was started at 2330 local time on 6 March 1939.

Fujibe (2011) reviewed urban climate studies in Japan focusing on long-term warming. Fujibe (2012a, 2012b) further reviewed more general features of urban climate in Japan. Mikami et al. (2011a, 2011b) edited a special issue on urban climate in the Japanese Journal of Geography, and Kanda (2012) edited review articles in the Japanese Meteorological Research Note. JMA has reported their heat island monitoring results every year since 2005, and the latest report was published in 2016 (JMA, 2016). Although excellent reviews have been conducted (*e.g.*, Arnfield, 2003; Collier, 2006; Roth, 2007), these recent Japanese results have not been well known, since some of them were written only in Japanese. The present paper reviews urban climate, mainly in the Tokyo metropolitan area in Japan.

1. Urban heat island

After the pioneering study of Fukui and Wada (1941), the temperature field of the Tokyo heat island was studied by many researchers from routine (*e.g.*, Maejima et al., 1980; Kawamura, 1985) and mobile observations (*e.g.*, Aida and Yaji, 1979; Yamashita, 1996). As JMA operates only 4 Automated Meteorological Data Acquisition System (AMeDAS) stations in central Tokyo, complementary information based on routine data has been collected using networks of Air Quality Monitoring System (AQMS) stations deployed by municipalities to study the urban climate (*e.g.*, Yamazoe and Ichinose, 1994; Mikami et al., 2004). As introduced by Yokoyama et al. (2008) and Akasaka et al. (2011), the Tokyo Metropolitan Research Institute for Environmental Protection (TMRIEP) and Tokyo Metropolitan University (TMU) established a system for dense temperature and other meteorological observations named the Meteorological Environmental Temperature and Rainfall Observation System (METROS) starting in 2002. The wider metropolitan area over the Kanto Plain has been covered by the Extended-METROS system since 2006. The results of these observations are presented in Fig. 3 (Mikami et al., 2011a, 2011b). Since Tokyo is located in the coastal area, and is affected by the Asian monsoon circulation, the temperature distribution in summer and winter is somewhat different, and the urban effect is masked by the local land-sea effect. Takahashi et al. (2011a, 2011b) and Takahashi and Takahashi (2013, 2014) used the surface pressure data of METROS to detect a pressure deficit in central Tokyo resulting from the hydrostatic effect of the nighttime heat island. The effect of sea breeze on the daytime urban heat island in summer was presented in Yamato et al. (2011). Takahashi et al. (2014) showed the detailed temperature distribution in the Tokyo metropolitan area under clear sky and weak wind conditions in winter. They pointed out different nighttime cooling conditions within the city, implying the effect of the inner city building structure. For the vertical structure of the heat island, Yoshikado and Kondo (1989) found an enhanced mixing layer in central Tokyo in the summer daytime.

Fig. 4 shows the departure of the annual mean temperature (Tmean) from the average during 1901–1920 at Tokyo and Hachijo Island (Hachijo-Jima) in the North Pacific, which is located 300 km south of Tokyo and may indicate the

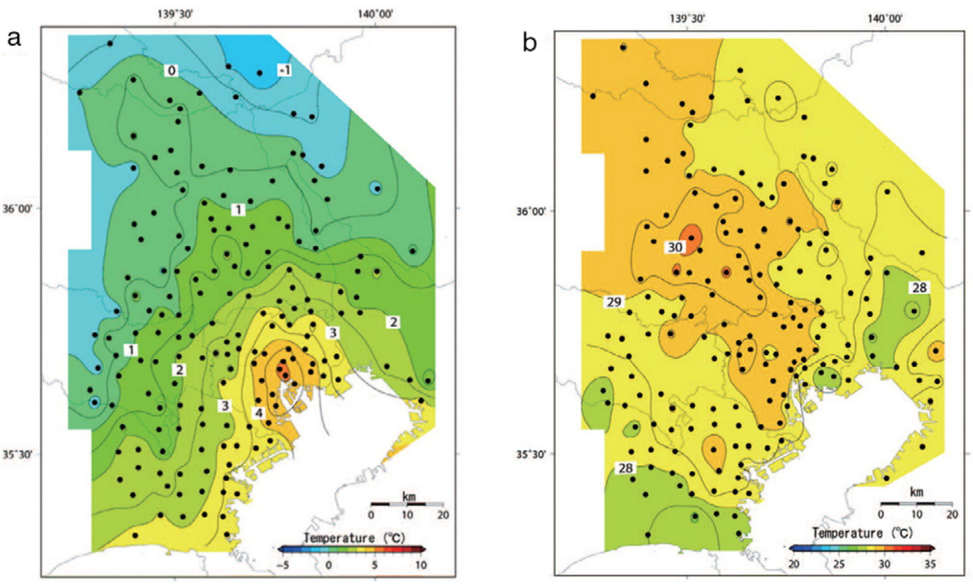

Fig. 3 – (a) Mean minimum temperature distribution in winter (December–February in 2007 and 2008) and (b) mean maximum temperature distribution in summer (August in 2006, June–August in 2007, and June–July in 2008) in the Tokyo Metropolitan area measured by the Extended-METROS system (unit: °C) (Mikami et al., 2011b).

near-natural variations in the south of Tokyo, together with the average of the 15 stations that are used by JMA for monitoring climate change across Japan. These stations are located in relatively small cities where population increase has not been obvious. The linear increase trend of annual mean temperature (Tmean) from 1901 to 2014 is 0.5°C/century for Hachijo-Jima, and 1.2°C/century for these 15 stations. In Tokyo, the increase is up to 3.0°C/century. According to the newest JMA information (JMA, 2016) increase of Tmean for the period 1931–2015 at Tokyo is 3.2°C/century, which is the largest among the 10 largest Japanese cities, and larger than the value of 1.4°C/century averaged by these 15 JMA stations. Temperature increase trends at Tokyo and at these 15 stations for the same period in the annual mean maximum temperature (Tmax) are 1.6 and 1.1°C/century respectively, and those in the annual mean minimum temperature (Tmin) are 4.4 and 1.8°C/century, respectively. It should also be noted that decadal-scale variations are observed at Hachijo-Jima, which indicates natural climate variability in the south of Japan. When compared with other East Asian cities shown in Table 1, temperature increase trends at Tokyo are close to those observed at Beijing for the period 1960–2000 (Ren et al., 2007) or at Seoul, South Korea for the period 1954–1999 (Jung et al., 2002), and somewhat larger than those at Taipei (Lai and Cheng, 2010) or Hong Kong (Ding et al., 2002).

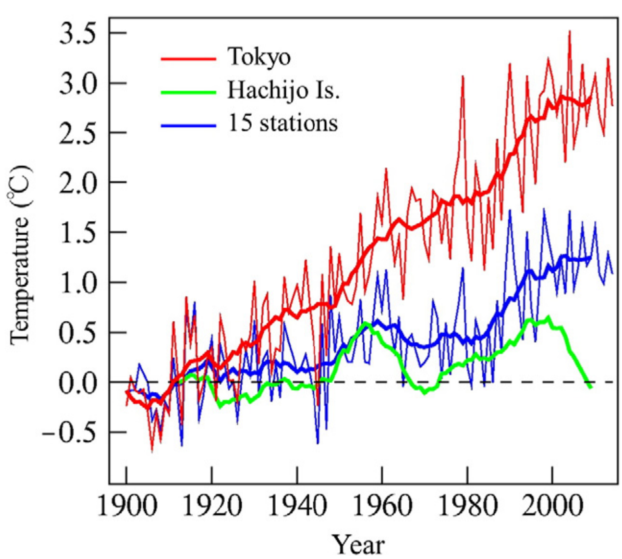

Fig. 4 – Time series of the departure of annual mean temperature (1901 to 2014) from the average for 1901–1920 at Tokyo and Hachijo Island (Hachijo-Jima), and from the average of 15 stations across Japan. Thin and thick lines indicate annual values and the 11-year running average, respectively.

A number of numerical studies based on mesoscale models incorporating urban parameterization reveal a widespread urban-induced anomaly of warm season daytime temperature around Tokyo (Kimura and Takahashi, 1991; Kusaka et al., 2000). According to these studies, this is a result of enhanced measurable heat due to reduced evapotranspiration over urban surfaces spreading for tens of kilometers. This feature, sometimes called the “extended heat island”, has a much larger horizontal dimension than the traditional heat island, which is normally confined to a single city. The extended heat island is characterized by a mixing layer with a height of ~1 km, so that the anomalous heat contained in the lower atmosphere is much larger than that of a nocturnal heat island. This heat content explains the increase in the amount of daytime pressure fall in Tokyo and the inland area at a rate of ~0.3 hPa/30 years, which corresponds to a mixing height of several hundred meters based on the hydrostatic relationship (Fujibe, 1994, 2003).

Table 1 – Temperature trends (°C/century) at major East Asian cities.

Country/region	Station	Tmean	Tmax	Tmin	Period	Source
Japan	Tokyo	3.2	1.6	4.4	1931–2015	JMA (2016)
China	Beijing	3.2			1961–2000	Ren et al. (2007)
China	Hong Kong	1.5			1947–1999	Ding et al. (2002)
South Korea	Seoul		2.4	4.0	1954–1999	Jung et al. (2002)
Taiwan	Taipei		1.22	2.08	1910–2005	Lai and Cheng (2010)

Tmean: annual mean temperature, Tmax: annual mean maximum temperature, Tmin: annual mean minimum temperature.

On a smaller scale, the urban heat island has considerable spatial variability corresponding to the urban substructure. A number of vegetated areas in Tokyo, such as the Imperial Palace and large parks, have been found to form cool islands with temperatures lower than the surrounding business areas by one or a few degrees (Hamada and Mikami, 1994; Narita et al., 2004; Sugawara et al., 2006, 2008, 2016; Nagatani et al., 2008; Narita and Sugawara, 2011). As introduced in Landsberg (1981), the cooling effect of urban green spaces such as large parks has been well known since Landsberg's (1956) description of such spaces as nature's air conditioner. It is commonly seen worldwide, as reviewed by Bowler et al., 2010). Interestingly, a year-round observation in and around Shinjuku Gyoen park reveals that the park is cooler than its surroundings in summer but warmer in the daytime during winter, possibly due to greater insolation under deciduous trees (Fig. 5; Sugawara et al., 2006). This is consistent with the results of another city at Nagoya, central Japan (Hamada and Ohta, 2010). On the other hand, in the case of Taipei, Taiwan (Chang et al., 2007), it was found that parks smaller than 7 ha are sometimes warmer than the surroundings regardless of the season. Japanese parks with deciduous trees may be responsible for the winter-time characteristics.

2. Urban rainfall

As reviewed by Shepherd (2005) and Collier (2006), numerous studies noted the influence of urban areas on precipitation. They, in general, pointed out the increase or intensification

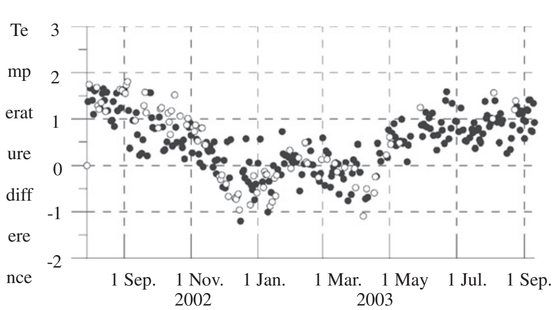

Fig. 5 – Daytime temperature difference between three sites outside a park (Shinjuku Gyoen) and two sites inside the park (Sugawara et al., 2006) in central Tokyo. Positive values indicate higher outside temperature. Open circles indicate no-rain days with fair weather and low wind, and closed circles indicate other no-rain days.

of precipitation in and around urban areas. Yonetani (1982) first noted the intensification of heavy daily rainfall in the Tokyo metropolitan area in August for the period from 1954 to 1976, when rapid urbanization occurred in Tokyo. Sato and Takahashi (2000) further noted the increase in heavy hourly precipitation exceeding 10 mm/hr for the period 1976–1998 in August. They also stated that such intensification was not detected in other summer months. Fujibe et al. (2009) analyzed the long-term trend of hourly precipitation in central Tokyo for 118 years (1890–2007). They found that no preceding precipitation (NPP) cases, defined as not preceded by ≧1 mm precipitation for the last 6 hr, showed an increasing trend of precipitation, and that prominent intensification occurred from afternoon to early evening during the warm season (Fig. 6). This result implies the intensification of convective precipitation by local urban heating.

On the other hand, Takahashi et al. (2011a) noted the spatial characteristics of heavy hourly precipitation by utilizing data from a dense rain-gauge network for the summer season (June to September) from 1991 to 2001 in Tokyo from various sources. They pointed out the high frequency of heavy rainfall areas in northern and western suburbs of the city center, which appeared to be localized by wind direction (Fig. 7). They suggested that this was due to the large surface roughness due to high-rise buildings, which affected the increasing frequency of intense rainfall. This is a mechanical effect of the urban structure. Kusaka et al. (2014) made a series of ensemble experiments of meteorological fields for eight August months (248 days for 2001 to 2008) in the Kanto area, using mesoscale models incorporating urban parameterization. Comparison of experiments with and without urban areas revealed an increase in the total precipitation amount in Tokyo and environs by 10%–20% due to urban effects (Fig. 8). A similar result was obtained by Seino et al. (2014). However, the response of precipitation activity to urban effects is highly chaotic, with some cases in which the precipitation amount decreases due to the presence of urban areas (Matheson and Ashie, 2008; Kusaka et al., 2009). It is therefore essential to deal with urban precipitation change from a statistical viewpoint, with attention to variability among cases. Takahashi (2003) and Kanae et al. (2004) have pointed out that precipitation intensification during the 1970s to 1990s is partly due to the decadal-scale climatic variations on a wider spatial scale, which can also be observed in Fig. 6 (left). On a centennial timescale, heavy precipitation is found to have increased in many regions of the world including Japan (Fujibe et al., 2006), corresponding to the increase in atmospheric water vapor due to global warming

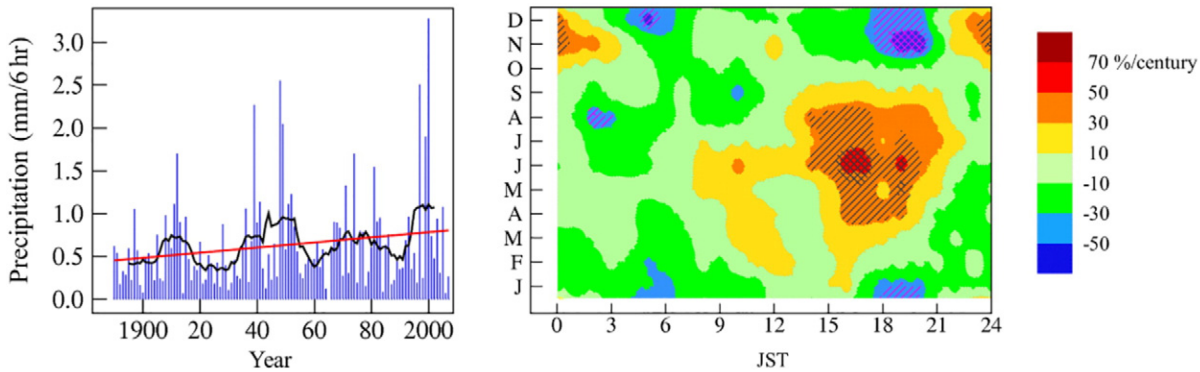

Fig. 6 – Long-term changes of hourly precipitation at Tokyo for the period 1890 to 2008. Left: six hourly precipitation amount for 1700–2300 JST from June to August averaged for all no preceding precipitation (NPP) cases. Each vertical blue bar denotes the value for each year, and black curve and red line indicate 11-year running mean and linear trend, respectively. Right: linear trend ratio per century for each time of the day and month for NPP cases. Hatching and double hatching denote that the trend is significant at 5% and 1% levels, respectively (Fujibe et al., 2009). JST: Japan Standard Time.

(IPCC, 2013). The interaction between these large-scale variations and local urban effects will be an important target for future studies.

3. Other phenomena

A cumulus cloud line is frequently observed just above Kanpachi Street (Ring road No. 8), one of the main traffic arteries of the Tokyo metropolitan area, running in the north–south direction on the western side of a high-density urban area. Kai et al. (1995) studied the surface meteorological conditions related to this cloud line. Kanda et al. (2001) conducted numerical simulations using the Regional Atmospheric Modelling System (RAMS) and found that the formation mechanism of this cloud line was related to both the local sea breeze circulation and urban heat island effect. An increase in cumulus clouds above the Tokyo metropolitan area is clearly seen in the satellite data during fine weather in the warm season (Fig. 9; Inoue and Kimura, 2004). The Normalized Difference Vegetation Index (NDVI) clearly shows the urbanized less-vegetated areas in the Tokyo metropolis indicated in the southern part of a broken line ellipse shown in Fig. 9a. Such less-vegetated areas expand northward in a spider-web-like fashion, which correspond to urbanized areas along the major train and highway lines in the suburbs of Tokyo. The higher low-level cloud amounts shown in a broken line ellipse in Fig. 9b correlated well with the low NDVI areas in Fig. 9a except in the near-coastal areas, where the sea breeze effect is predominant.

The number of fog days increased from 1920 to 1940, then decreased to low-levels after the late 1970s in Tokyo (Fig. 10; Fujibe, 2012a). There was an increase in fog days in the 1920s and 1930s mainly during the cold season, as indicated in

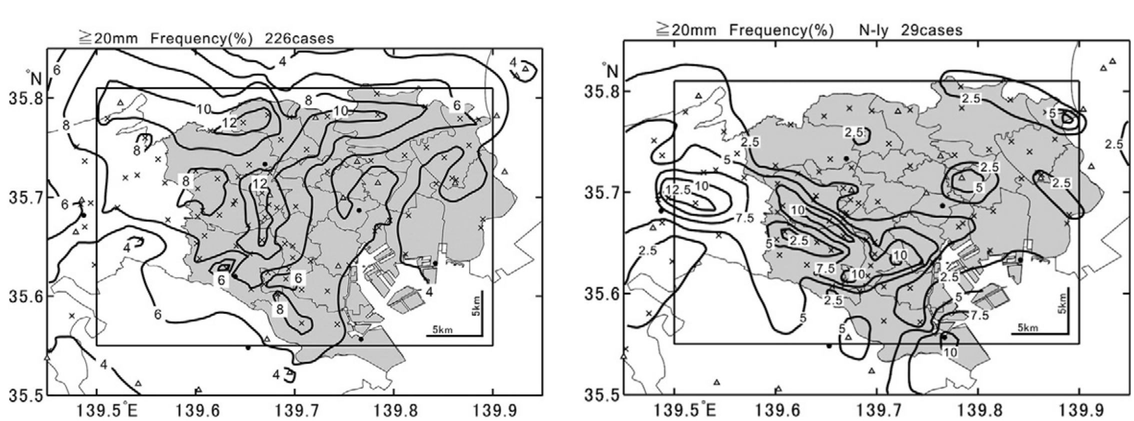

Fig. 7 – Frequency distribution of intense rainfall (20 mm/hr) in the central Tokyo. The values represent the percentage frequency calculated as a ratio of the number of cases of intense rainfall at each rain-gauge station to the total number of cases of intense rainfall that occurred in the target area (totaling 226 cases). The gray area indicates the area comprising the wards of the Tokyo Metropolis. Left: total frequency, right: for the cases that wind direction at the Japan Meteorological Agency (JMA) headquarter is northerly (29 cases) (Takahashi et al., 2011a). JMA: Japan Meteorological Agency.

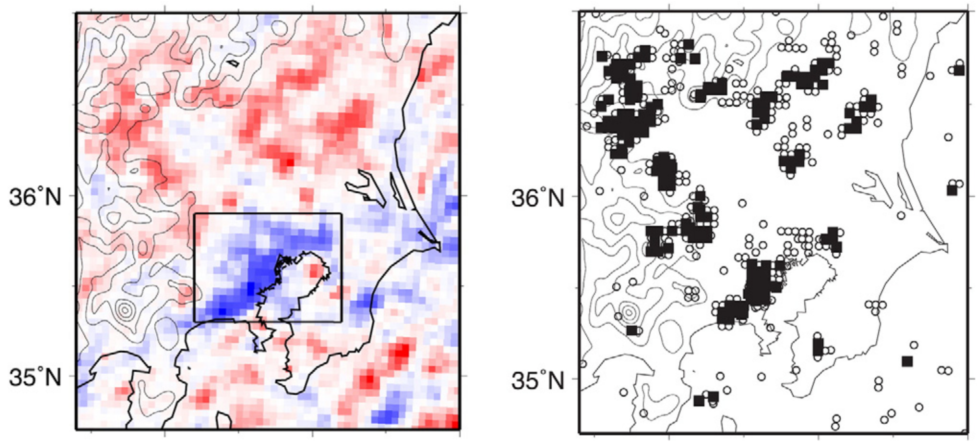

Fig. 8 – Left: simulated urban impacts (anomalies from non-urban case) on the monthly precipitation amount in August during 2001–2008 for a case in which urban surface parameters such as building height and anthropogenic heat values were taken as average values from the present-day Tokyo. Right: results of the Wilcoxon *t*-test of statistical significance for the left figure. Solid squares and open circles indicate significance levels of 99% and 95%, respectively (Kusaka et al., 2014).

Fig. 9. Very dense fog was also observed in the 1930s in Tokyo. This increase in fog was due to coal burning. More stable conditions and less precipitation during the cold season in Tokyo also favored the increase of fog. After the 1960s, the main source of Japanese fuel changed from coal to oil. In addition, air pollution regulation was reinforced and is one of the main reasons for the rapid decrease of fog after the 1970s. The temporal change pattern is similar to that observed in London from the 19th to the 20th century shown by Brimblecombe (1981, 1987). The annual mean relative humidity at Tokyo was approximately 70% at the beginning of the 20th century, and rapidly decreased from the 1950s to the late 1960s to approximately 65% (Omoto et al., 1994), part of which may be related to the decrease in fog days presented in Fig. 10. The decrease in relative humidity is mainly attributed to the temperature increase and the resulting increase in saturated vapor amount, whereas the annual mean vapor pressure is also found to have decreased in Tokyo since 1931 with a rate of 0.6 hPa/century (JMA, 2013). A traverse observation by Aida and Yaji (1979) on a winter night clearly showed lower vapor pressure in Tokyo than in the surroundings. On the other hand, a recent increase of both relative humidity and vapor pressure during the daytime on hot summer days has been detected (Fujibe, 2002). This feature is in accordance with a large moisture flux observed in the central business area (Ginza) in midsummer, possibly due to water vapor emission from air-conditioned buildings (Kanda et al., 1997). Using a regional climate model, Takahashi et al. (2015) showed that the increase in the sea surface temperature in the Kuroshio region in the south of the Pacific coast of Japan induces a higher temperature. This is particularly noticeable at nighttime during summer, because of the increase of H_2O greenhouse gas, demonstrating that water vapor is an important factor affecting the urban climate. On the other hand, Ohashi and Kida (2004) showed that an urban heat island circulation associated with a local mountain–valley circulation may lead

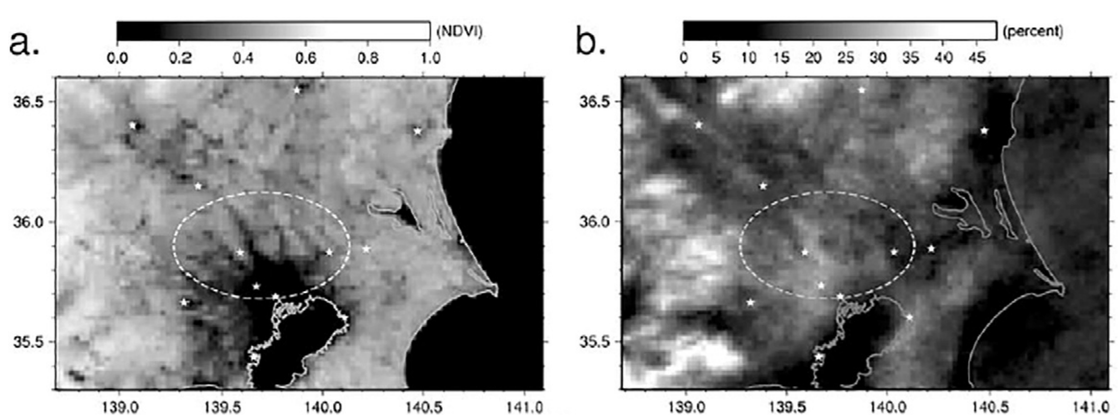

Fig. 9 – (a) Normalized Difference Vegetation Index (NDVI) during summer in 1991; (b) Low-level cloud frequency by 1 km resolution National Oceanic and Atmospheric Administration (NOAA) Satellite observation on 328 clear days during April–October in 1990–2000. Lighter shading indicates higher NDVI (a) and higher low-level cloud frequency (b). The ellipses shown in broken lines indicate the characteristic Tokyo metropolitan urban areas (Inoue and Kimura, 2004).

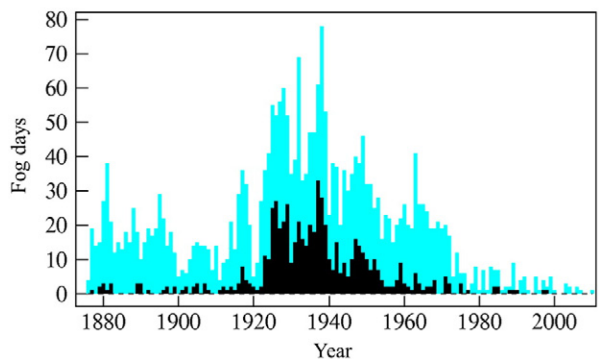

Fig. 10 – Annual number of fog days in Tokyo (1876–2010) based on JMA observations. Black bars indicate fog days in winter (Jan., Feb. and Dec.) (Fujibe, 2012a).

to drying over suburban areas away from the city center in the inland city Kyoto, western Japan, using a mesoscale model. Fujibe and Asai (1980) statistically showed the existence of a converging wind field in Tokyo. It seemed to correspond to a local circulation induced by the urban heat island, even though the wind was very weak (~0.2 m/sec) and possibly affected by the sea breeze. Later, Fujibe (1988) detected the difference in the intensity of converging winds between weekdays and holidays, confirming the contribution of urbanization. Yoshikado (1994) used a two-dimensional (2D) model to simulate the interactions between a sea breeze circulation and a heat island circulation in Japan. Recent numerical studies have shown a change in summer daytime wind fields in the Tokyo metropolitan area, with a convergence line on its inland side due to the interaction of the extended heat island and the sea breeze (*e.g.*, Kusaka et al., 2000). Comparison of wind fields in the 1920s and the 1990s also revealed a change in the sense of increasing convergence toward the center of the Kanto Plain in the daytime of the warm season (Fujibe, 2003). For winter, the heat island in Tokyo is found to generate a condition favorable for the onset of a sea breeze in spite of the relatively warm sea surface (Yoshikado and Tsuchida, 1996).

4. Conclusions

The Tokyo metropolitan area in Japan has experienced rapid growth since the Meiji era in 1868, which was interrupted only during the WWII period. Long-term climate changes related to the urbanization in Tokyo and recent temperature and heavy rainfall distribution in the Tokyo metropolitan area are reviewed. A relatively high temperature increase in annual mean temperature at the rate of 3.0°C/century was detected at Tokyo for the period 1901–2015. Some observational evidence shows the existence of both thermal and mechanical effects of urbanization on heavy rainfall occurrences, while modeling studies support precipitation enhancement. However, due to the chaotic nature of convection, further detailed studies are needed to specify the effect of urbanization on precipitation.

Urban influences are recognized in other climatological elements, such as number of fog days, relative humidity, and wind circulation. For example, the number of foggy days in Tokyo increased in the 1920s and 1930s then decreased after the 1980s. These results are, in general, consistent with findings in other cities, but some specific features are noted peculiar to the mid-latitude monsoon climate and environment in Tokyo. There are decadal-scale climate variations, which sometimes make it difficult to detect the pure urban effects on climate. Further studies are needed on the effect of decadal-scale climatic variations.

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