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LONG-TERM CHANGES IN WEEKDAY-HOLIDAY TEMPERATURE DIFFERENCE IN CENTRAL TOKYO: ANALYSIS SINCE THE EARLY 20TH CENTURY

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Abstract To analyze the long-term trends of weekday-holiday temperature differences in Tokyo, Japan, meteorological data obtained from 1897 to 2021 were used. Negative departure of temperature on holidays from that on weekdays (*ΔT*) was determined for the period after the 1960s. From 1970 to 1990, *ΔT* had a value of –0.15 to –0.2 °C and –0.2 to –0.3 °C for the daily mean and daily maximum temperatures, respectively. Moreover, a decline in trend of *ΔT* emerged after the 2000s. Prior to 1960 *ΔT* was generally less; however, positive values of approximately 0.1 °C were determined as the daily maximum temperature from 1920 to early 1930s, accompanied by a positive anomaly of the frequency of light precipitation defined by a daily precipitation between 0.1 and 1 mm.

Keywords: weekday-holiday temperature difference, weekly cycle, urban temperature, urban climate, Tokyo

1. Introduction

Anthropogenic activity can alter local climates, and several cities worldwide are known to have lower air temperature during the holidays than on weekdays (Earl *et al.* 2016), apparently due to reduction in anthropogenic heat release. As “week cycling” is an artificial concept, the weekly variation in meteorological elements is convincing evidence that anthropogenic activity affects the atmosphere provided that statistical verification is conducted properly, although it may be challenging to distinguish the natural cycles that occur within seven days (Ohashi *et al.* 2016; Jiang and Wang 2018).

Tokyo is the capital of Japan with a population of nearly ten million. Fujibe (1987) reported that the temperature in central Tokyo was lower on holidays than on weekdays by approximately 0.2 and 0.1 °C in the daytime and nighttime, respectively, on an average within 1961 to 1985. A similar result was obtained by Fujibe (2010) for the period from 1979 to 2008. Additionally, Fujibe (2020) showed that the temperature in central Tokyo was lower than that in an ordinary state by approximately 0.5 °C during a period of suppressed social activity during the COVID-19 pandemic in 2020. However, consequent to lapses in data availability, analysis for the period before 1960 has not been performed. In fact, Tokyo has been a million-city since the early 20th century (Fig. 2a), and its urban climate has been recognized since the 1930s. For example, in 1939 a distinct heat island in the city was reported by Fukui and Wada (1941). Therefore, determining the weekday-holiday temperature difference in Tokyo since the beginning of the 20th century is

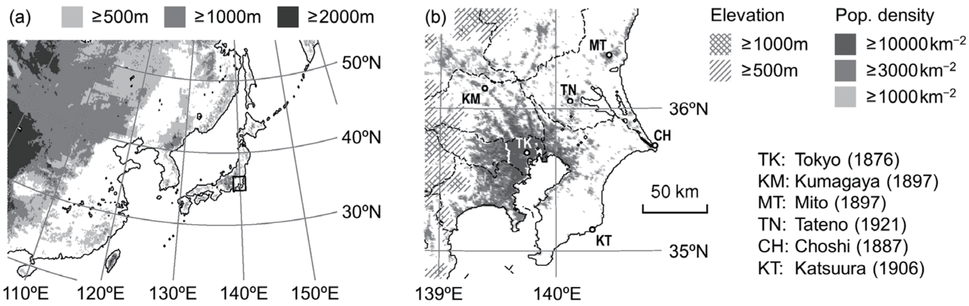

Fig. 1 (a) Map of East Asia. The region shown in (b) is indicated by a square. (b) Map of the area around Tokyo. Dashed lines indicate the boundaries of prefectures, and white lines indicate the western border of the Tokyo Wards Area. The population density is based on the National Census in 2015. Stations used for analysis are displayed as small circles, and their names are located at the bottom right of the panel. The parentheses indicate the first year in which data became available.

interesting.

Recently, the Japan Meteorological Agency (JMA) has digitized daily temperature and precipitation data at synoptic observation stations since their foundation. In this study, these data were used to analyze the differences in temperature and precipitation between weekdays and holidays in central Tokyo since the early 20th century.

2. Data and Procedure of Analysis

Background information

Official meteorological services in Japan started in the 1870s. Notably, over 80 weather observatories were deployed in the country by the end of the 19th century, and approximately 150 stations were established by the mid-20th century. The data of daily mean, maximum, and minimum temperatures, as well as daily precipitation obtained at these stations for their entire operation duration are available in digital formats.

Tokyo Metropolis (Tokyo-*to*) is located in the central part of the Kanto Plain, which lies in the southeastern region of Honshu, the main island of Japan (Fig. 1). The eastern region of Tokyo Metropolis is the Tokyo Wards Area (TWA) that was reorganized from Tokyo City into an aggregate of “special wards” in 1943. Presently, the area of TWA is determined to be 628 km^2. Figure 2a displays the time series of the population of Tokyo City and TWA. The population increased in the first half of the 20th century, except for a decline during World War II, and has remained between eight and ten million since the 1960s.

The observatory of Tokyo was founded in 1875 and is located in the central part of TWA until recently, with some relocation. The annual mean temperature in this area has increased by approximately 3 °C $century^{-1}$ from the 20th to early 21st century, indicating an urban warming and global change of approximately 2 and 1 °C $century^{-1}$, respectively (Matsumoto *et al.* 2017). In December 2014, the observation field was relocated from Otemachi, which was a business area, to Kitanomaru Park, which is a large vegetated area. The distance between the two stations was

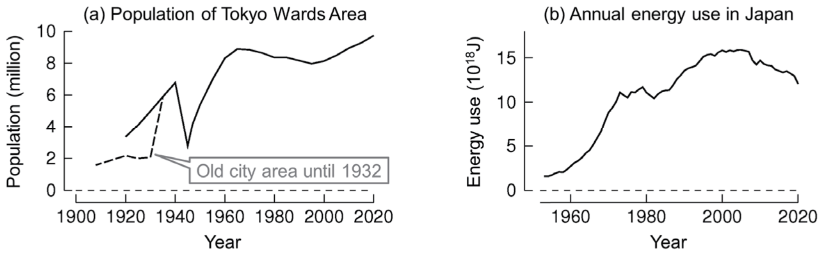

Fig. 2 (a) Population of the former Tokyo City and Tokyo Wards Area (TWA) based on census data for 1908–2020. The dashed line indicates the population of the old city area until 1932, over an area that consists of 14% of the present TWA. (b) Annual energy use in Japan based on the ANRE data for 1953–2020.

900 m; however, the daily mean, maximum, and minimum temperatures at the new site were found to be lower than those of the old site by 0.9°, 0.2°, and 1.4 °C, respectively (JMA *et al.* 2016).

Figure 2b shows the time series of energy use in Japan from 1953 to 2020 obtained from data published by the Agency for Natural Resources and Energy (ANRE; https://www.enecho.meti.go.jp/about/whitepaper/2022/html/; https://www.enecho.meti.go.jp/statistics/total_energy/ (August 23rd, 2022)). The figure shows that there was a rapid increase in the 1960s corresponding to an economic growth, followed by a gradual increase from the 1970s to 2000s. After the late 2000s, the energy utilization declined. According to ANRE (2018), the energy utilization in Japan before 1950 was much lower than that after the 1960s.

The conventional weekly cycle was introduced in Japan during the late 19th century. Consequently, many government offices, companies and schools have been closed on Sundays, as well as on national holidays and the first three days of the New Year. Data of historical national holidays were obtained from the National Astronomical Observatory of Japan (2021). Since 1973, if a national holiday falls on a Sunday, the following Monday has been made a substitute holiday. Furthermore, many offices and schools were also closed in the afternoon on Saturdays, and since the 1980s, most organizations do not work on Saturdays.

Data

Data of daily temperature (average, maximum, and minimum) and precipitation at Tokyo and five nearby stations were used (Fig. 1). These five stations were used as a reference in a way described in the next section. The precision of temperature observation was 0.1 °C. The daily average temperature is the mean of the temperatures observed several times a day. For precipitation, the observation precision was 0.1 and 0.5 mm until the early 1960s and thereafter, respectively.

Procedure of analysis

Analysis was conducted for the daily mean temperature (T_{mean}), daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), and daily temperature range (DTR), as well as the daily precipitation frequency (P_{1mm}) defined by the percentage of days on which the amount of precipitation was 1 mm or more. For the period until 1963, by when 0.1 mm precision data were available in Tokyo, the light precipitation frequency ($P_{<1mm}$) was defined by the percentage of days on which the amount of precipitation was at least 0.1 mm and less than 1 mm.

Weekdays were defined as Monday through Friday. Notably, national holidays, substitute holidays, and the first three days of the New Year were excluded from the statistics for weekdays and Saturdays and were considered as holidays, including Sundays. To eliminate the synoptic cycle, the analysis was based on the departure of the temperature on a holiday from the temperature that would have been observed if it were a weekday. The procedure is as follows: first, a regression analysis was conducted to create an equation for interpolating the weekday temperature at Tokyo from the temperatures obtained at reference locations. The regression criterion is as follows

$$\sum_{\text{weekdays}} (x_0 - \sum_{i=1}^{n} a_i x_i)^2 \rightarrow \text{min.},$$

with the condition $\sum_{i=1}^{n} a_i = 1$, where x_0 and x_i are the observed temperatures in Tokyo at the i-th reference station ($i = 1, \cdots, n$), respectively, and a_i is the least-squares coefficient. Thereafter the least-squares coefficients were applied to holidays as $x_1 = \sum_{i=1}^{n} a_i x_i$, which gave the estimated temperature at Tokyo on weekdays. The difference between x_1 and the observed holiday temperature in Tokyo, namely $x_q = x_0 - x_1$, was used as an index of temperature deviation on holidays with respect to weekdays.

The analysis began from 1897, from when data at the three reference stations (Mito, Kumagaya, and Choshi) were available. Data obtained at Katsuura and Tateno were used from their foundations, since 1906 and 1921, respectively. The analysis ended in 2021. To evaluate x_q with sufficient confidence, these procedures were applied to a period of 15 years with a half width of 7 years before and after each year; therefore, x_q was available from 1904 to 2014. Since the number of national holidays differs according to months, the procedures were applied to each month to obtain monthly x_q values first, followed by determining the average to obtain x_q for the entire year or season. Thereafter x_q for T_{mean}, T_{max}, and T_{min} would be denoted by ΔT_{mean}, ΔT_{max}, and ΔT_{min}, respectively.

A similar method was applied to *DTR*, P_{1mm} and $P_{<1mm}$, and to other days of the week. The analyses for Sundays excluding holidays were also made; however, the results are not shown in this study because they do not differ significantly from those obtained including holidays.

Notably, there have been some changes in the instruments and observation schedules for temperature and precipitation, and these changes can be accompanied by some observational bias. However, no correction was made in this study because such bias, if any, is likely to be eliminated by the difference between weekdays and holidays. Furthermore, the analysis was based on an assumption that weekday-holiday differences at the reference stations were negligible. This assumption is justified in view of the results by Fujibe (2010), which demonstrated that weekday-holiday temperature differences at stations where the population density of the surrounding area was 1000–3000 km^2, corresponding to medium-sized cities such as Mito and Kumagaya, which were an order of magnitude smaller than that at Tokyo.

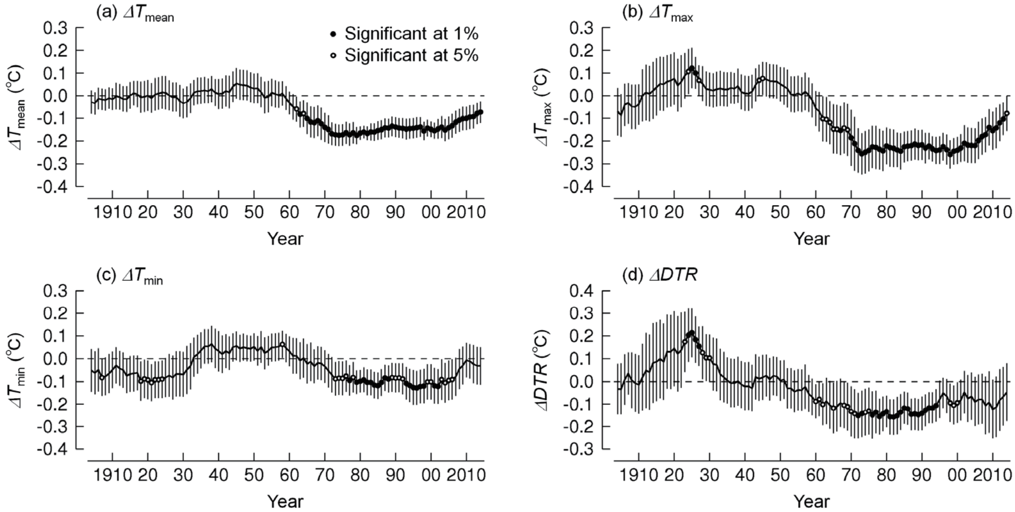

Fig. 3 Time series of (a) ΔT_{mean}, (b) ΔT_{max}, (c) ΔT_{min}, and (d) ΔDTR on holidays evaluated for a 15-year interval centered on each year from 1904 to 2014. Vertical bars indicate the 95% confidence range. Open and closed circles indicate statistically significant values at the 5% and 1% levels, respectively.

3. Results

Figure 3 shows the time series of ΔT_{mean}, ΔT_{max}, ΔT_{min}, and ΔDTR for holidays on the annual average. In the 1960s, ΔT_{mean} and ΔT_{max} had negative values, and remained between approximately –0.15 to –0.2 °C and –0.2 to –0.3 °C, respectively, from the 1970s to 1990s. Similar changes could be seen for ΔT_{min} although the absolute values were smaller, and ΔDTR had statistically significant negative values from the 1960s onward. The values of these quantities have declined since the 2000s.

The four quantities were generally small until the 1950s. However, ΔT_{max} had positive values of approximately 0.1 °C in the 1920s. Meanwhile ΔT_{min} had negative values, and consequently, ΔDTR had positive anomaly reaching 0.2 °C during this period.

Figure 4 shows the time series of ΔT_{mean} and ΔT_{max} for Saturdays and Mondays. For Saturdays, ΔT_{mean} and ΔT_{max} were negative since the 1960s and 1980s, respectively. By the year 1990, both parameters had a value of –0.1 and –0.15 °C, respectively, which subsequently declined. For Mondays, negative anomalies of ΔT_{mean} and ΔT_{max} were present in the 1990s and 2000s, respectively, which is consistent with the finding of Fujibe (2010). Notably, the substitute holidays have been excluded from the statistics for ΔT on Mondays.

Figure 5 shows the weekly variations of ΔT_{mean} and ΔT_{max} at an interval of 15 years since 1965. Note that the values for 1965 were obtained from statistics over the 15 years from 1958 to 1972. Negative values are clearly seen for holidays, and for Saturdays and Mondays in some periods.

Figure 6 shows the weekly variations of ΔT_{mean} and ΔT_{max} for the year 1995 (calculated from the statistics for 1988–2002) during each season. Statistically significant negative values are seen for holidays in all seasons except for winter. Even for winter, ΔT_{max} had negative values that are significant at a 1% level from the late 1970s to mid-1980s, as well as in the 2000s (not shown).

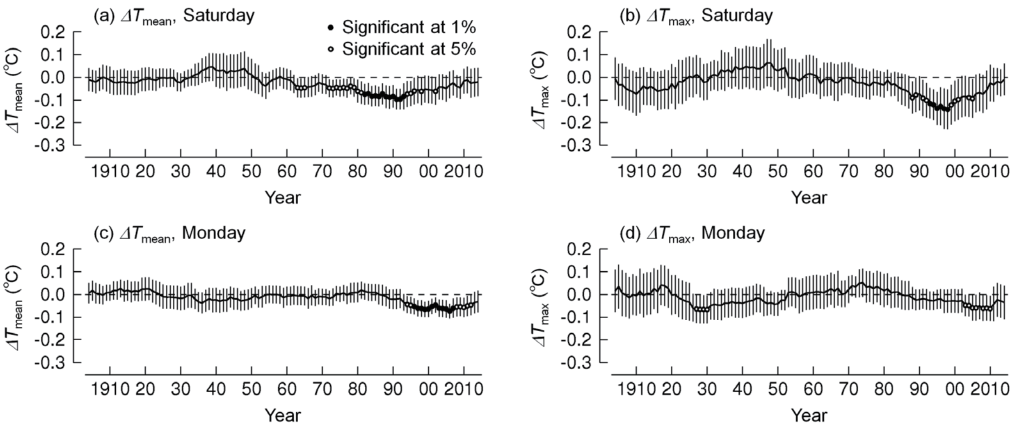

Fig. 4 Same as in Fig. 3 but for (a) ΔT_{mean} on Saturdays, (b) ΔT_{max} on Saturdays, (c) ΔT_{mean} on Mondays, and (d) ΔT_{max} on Mondays.

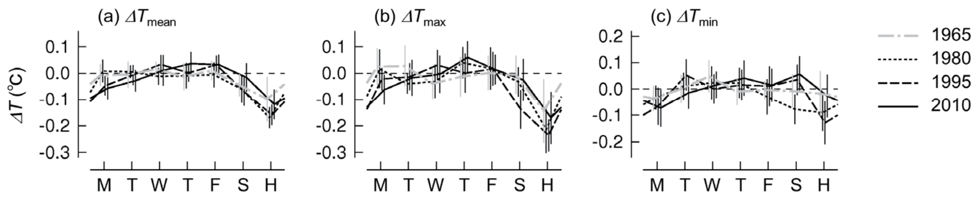

Fig. 5 Weekly cycles of ΔT_{mean}, ΔT_{max}, and ΔT_{min} evaluated for a 15-year interval centered on 1965, 1980, 1995, and 2010. Days of the week are indicated by Monday-Saturday (M-S) and holiday (H). Vertical bars indicate the 95% confidence range.

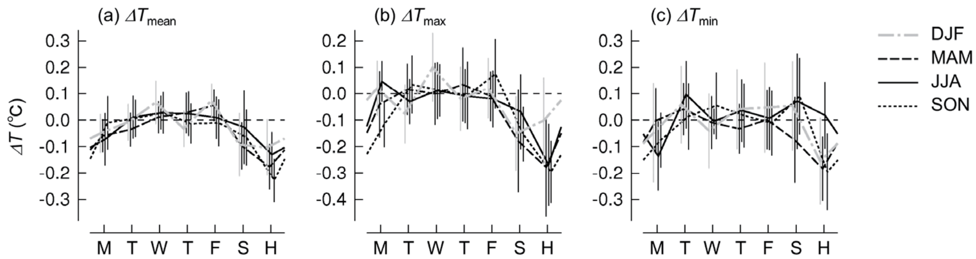

Fig. 6 Same as in Fig. 5 but for each season for a 15-year interval centered on 1995.

Figure 7 shows the time series of ΔP_{1mm} and $\Delta P_{<1mm}$. Only a few significant values are obtained for ΔP_{1mm}, while $\Delta P_{<1mm}$ showed positive values of 0.02 to 0.03 in the 1920s, partly significant at the 1% level. The value of 0.02 indicates that the frequency of <1 mm precipitation was 2% higher on holidays than on weekdays.

Figure 8 shows the weekly variations of ΔT_{max}, ΔDTR, ΔP_{1mm}, and $\Delta P_{<1mm}$ for the year 1925 (calculated from the statistics for 1918–1932). Except for ΔP_{1mm}, statistically significant positive values are seen for holidays.

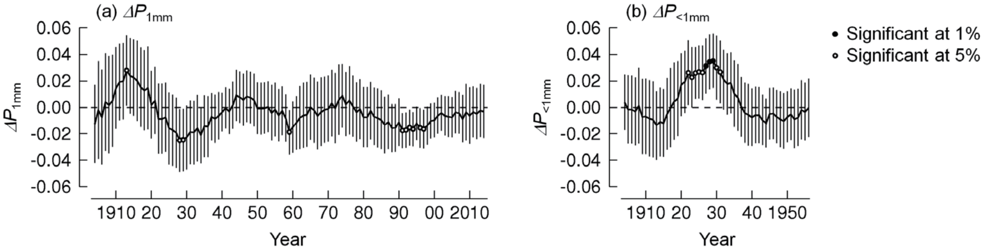

Fig. 7 Same as in Fig. 3 but for (a) ΔP_{1mm} and (b) $\Delta P_{<1mm}$ on holidays. The time period in (b) is from 1904 to 1956.

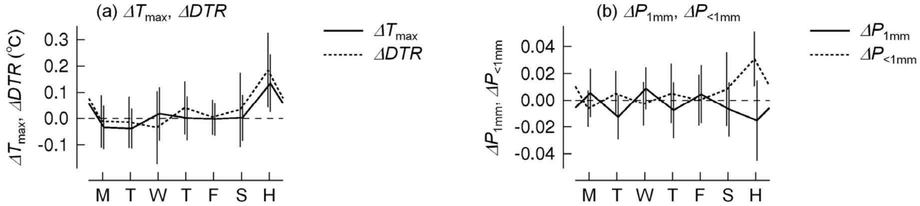

Fig. 8 Same as in Fig. 5 but for (a) ΔT_{max} and ΔDTR, and (b) ΔP_{1mm} and $\Delta P_{<1mm}$ for a 15-year interval centered on 1925.

4. Discussion

This study demonstrated that the temperature departure on holidays from that on weekdays (ΔT) became notable in Tokyo after the 1960s. From the 1970s to 1990s, ΔT remained nearly constant with values of –0.15 to –0.2 °C for ΔT_{mean} and –0.2 to –0.3 °C for ΔT_{max}. Moreover, since the 2000s ΔT has declined, and these changes in ΔT are qualitatively consistent with the trends in energy utilization shown in Fig. 2b.

However, this reduction in ΔT has been more apparent than the decline in energy consumption. During this period, the observation field of Tokyo was relocated from Otemachi to Kitanomaru Park in December 2014. Thus, data from 2015 onward were observed at Kitanomaru Park. Since the analysis was based on a 15-year window with a half width of 7 years, the data obtained at Kitanomaru could only be effective from 2008. As seen in Fig. 3, ΔT on holidays appears to have declined from 2005, specifically before the relocation could have taken effect. Nevertheless, the statistical uncertainty in ΔT issues a challenge to establish a definite conclusion, whereas the effect of the relocation cannot be completely ruled out even if other factors were involved in the reduction of ΔT. Considering that the site change affected ΔT implies that a large difference in ΔT existed within a distance of less than 1 km, indicating small-scale non-uniformity in the effect of anthropogenic heat on air temperature. Therefore, the relationship between the site change and ΔT is an interesting focus for future research on the spatial scale of urban climate.

Negative ΔT values are more apparent for ΔT_{max} than for ΔT_{min}, in agreement with the larger absolute values of ΔT obtained during the daytime than in nighttime (Fujibe 2010). Seasonally, negative values of ΔT were found in all seasons; however, this is less evident in winter. Ohashi *et al.* (2016) suggested that the cool air emitted from heat-pump air conditioning might result in the reduction or reversal of weekday-holiday temperature difference in the central city during winters.

However, a more detailed analysis would be required to verify this assumption.

The study has shown that ΔT was generally small until the 1950s, except for a short period around the 1920s. This is consistent with the small amount of energy consumption in Japan before the 1950s (ANRE 2018; Fig. 2b). Exceptionally, positive values of ΔT_{max} and $\Delta P_{<1mm}$, as well as negative T_{min} anomalies were found in the 1920s. Meanwhile, Tokyo was posed with heavy air pollution and an increasing number of fog days that occasionally exceeded 50 days in some years (Matsumoto *et al.* 2017). One could possibly speculate that the positive ΔT_{max} value was due to the low air pollution and strong insolation on holidays. However, it is challenging to interpret the positive anomaly of $P_{<1mm}$. Yoshino (1957) showed that the number of light precipitation days (0.1–1 mm) was high in central Tokyo, using the observation data obtained in 1943. This result implies that the urban effect may have affected light precipitation; however, the physical explanation is a subject for future research.

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