Long-term Change and Spatial Anomaly of Warm Season Afternoon Precipitation in Tokyo

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Abstract

The long-term trend of precipitation at the central part of Tokyo was analyzed using digitized hourly data for 118 years (1890–2007). It was found that "no preceding precipitation" (NPP) cases, defined as not preceded by ≥1 mm precipitation for the last six hours, showed an increasing trend of precipitation as a rate of 30%/century or more from afternoon to early evening of the warm season. Analysis for spatial precipitation patterns for NPP cases, using hourly data on the AMeDAS network for the recent 30 years (1978–2007), also showed a positive anomaly in Tokyo in the afternoon of the warm season. These facts suggest the reality of the urban heat-island effect on the increase of warm season short-term precipitation in Tokyo.

1. Introduction

The precipitation change in cities is a controversial problem in urban climatology. It is no wonder that excessive heat supply from the urban surface and a resulting local circulation favor the formation and development of convective clouds. A number of observational studies for cities in the United States and Mexico have revealed the increase or spatial anomaly of convective activity in the afternoon of summer, in which urban thermal forcing is believed to be pronounced as excessive surface heating (e.g., Changnon 1981; Westcott 1995; Jauregui and Romales 1996).

The Tokyo metropolitan area is characterized by a high degree of urbanization, with rapid temperature increase amounting to 3°C per century (e.g., Fujibe 2008b). Inoue and Kimura (2004, 2007) showed a close relationship between daytime cloud amount and land use over the northern outskirts of Tokyo, indicating urban influences on cloud formation. However, urban signals in precipitation distribution are less distinct, apart from some indication of spatial anomaly and local enhancement of convective systems (Fujibe 1998; Sato et al. 2006). As for long-term changes, some researchers have shown the increase of intense precipitation in Tokyo on the time scale of a few decades (Yonetani 1982, 1989; Sato and Takahashi 2000), whereas Kanae et al. (2004) has revealed the dominance of multi-decadal variation in heavy precipitation using a 110-year time series of hourly data at Tokyo. Moreover, recent studies have shown that increase of intense precipitation is a nation-wide feature (Fujibe et al. 2005, 2006; Fujibe 2008a), without a clear signal of urban anomaly.

Thus, there is still much room to investigate the precipitation change in Tokyo and its relation to urbanization. It is to be noted that the majority of heavy rainfall events in Japan are caused by cloud systems associated with large-scale disturbances, which are not likely to be affected by urban processes. This situation requires more detailed analysis focused on short-term, localized precipitation in the warm season in order to detect urban influences on precipitation activity. The consistency between long-term change and spatial anomaly of urban precipitation also deserves further research.

In a joint research project of the Meteorological Research Institute and the Tokyo District Meteorological Observatory (TDMO), hourly precipitation data at Tokyo have been digitized for the period since 1890. The aim of the present study is to examine urban signals in long-term precipitation changes in Tokyo based on an analysis targeted to cases favorable for a strong heat-island effect. To meet this purpose, analysis was made for cases that were not preceded by precipitation, as detailed in the next section. At the same time, 30-year data on the network of AMeDAS (Automated Meteorological Data Acquisition System), having a horizontal resolution of 15–20 km, were used to examine the precipitation distribution in search of consistency between temporal and spatial features.

2. Precipitation trends for 118 years at Tokyo

2.1 Data and procedure of analysis

Hourly precipitation data at Tokyo were obtained from the data files of AMeDAS and synoptic observations for the period from 1975 to 2007. For the period before 1975, data were digitized from surface observation records down to 1890, from which hourly records were available from the Observations Department of the JMA. For 1953 to 1955, hourly data of the "specified climatological observation" were used, because the record of surface observation was only three hourly. The data were fully quality-checked with one-by-one comparison to the original record. Thus we have obtained nearly complete hourly records for 118 years (1,034,376 hours), with 430 missing values that are mainly found from 1964 to 1965.

The observation site is at Otemachi, in the central part of the city (see Fig. 4 for location), after it moved by about 600 m eastward in 1923. The resolution of observation changed from 0.1 mm to 0.5 mm in October 1964, as the traditional rain gauge was replaced by the tipping-bucket one, although the former was used again from 1966 to 1967 to measure the precipitation below 0.5 mm. For the period from 1975 to 1988, data are recorded at a 1 mm resolution.

The analysis was made for six-hourly precipitation, obtained by a running sum of hourly values, because intense precipitation systems in Tokyo tend to last for a few hours or more (e.g., Seko et al. 2007). Data were reduced to the 1 mm resolution, on the assumption of no evaporation from the tipping bucket.

As suggested so far (Changnon 1981; Westcott 1995;
2.2 Results

Figure 1a shows the time series of NPP precipitation for 1700 to 2300 JST for the three months from June to August. There is considerable year-to-year variability, as well as multidecadal changes as seen from the curve of 11-year running mean. In addition to these variations, there is apparently an increasing trend with time. In order to evaluate the linear trend, a least-squares fitting was made as

\[ \sum_{n} \left( \frac{P(n) - \left\{ A + B \left( n - \frac{n_{1} + n_{2}}{2} \right) \right\}}{\sum_{n}} \right)^{2} \rightarrow \min, \]  

where \( n_{1} \) and \( n_{2} \) are the first and last years of the analysis period (i.e., 1890 and 2007), \( A \) is the least-squares coefficient indicating the long-term mean, and \( B \) that indicating the trend. The relative trend \( B/A \) is 48%/century, with a 95% confidence range of 47%/century. The statistical significance was evaluated by applying the \( t \)-distribution to the residual terms in (1), on the assumption of normal distribution of the residuals.

Figure 2 shows the trend for each time of the day and month, obtained by applying (1) for each six-hour period for three consecutive months. A positive trend exceeding 30%/century is found mainly from late afternoon to early evening of the warm season.

For the sake of comparison, the result for all the cases is shown in Figs. 1b and 3. The trend is much weaker (~10%/century at most) than for NPP cases, although there are considerable year-to-year and multidecadal variations. Thus the increasing trend of precipitation at central Tokyo is characteristic to NPP cases in the afternoon of the warm season.

Similar analyses were made for precipitation frequency above some criteria. The results for 3–10 mm/6h precipitation have qualitatively the same feature as obtained for precipitation amount (Fig. 2), as shown in the Supplement file. Analyses were made also for hourly, three-hourly, and nine-hourly precipitation in defining NPP cases, instead of six-hourly precipitation, as well as for \( P(n)^{m} \) instead of \( P(n) \), in order to examine the effect of deviation from the normal distribution of the residual terms in (1). It was found that these modifications did not alter the results essentially, as described in the Supplement file.

3. Spatial anomaly of precipitation in Tokyo

The analysis of AMeDAS data was made for the period from 1978, by which most of the stations had been deployed in and around Tokyo, to 2007. Three stations, Otemachi, Nerima, and Setagaya, are located in the highly urbanized area of Tokyo (Fig. 4). The station at Otemachi is the same as that used for the analysis in Section 2.

Six-hourly precipitation was obtained by a running sum of hourly values. Stations at which missing data were more than 5% in any of the twelve months were not used for analysis. The definition of NPP case was based on the percentage of stations at which precipitation of 1 mm or more was observed during the preceding six hours over the Kanto plain, where data at 62 stations were available at altitude below 150 m. An NPP case requires that the percentage of such stations should be less than 10%.

Figure 4 shows the precipitation distribution in NPP cases for 1700–2300 JST of June to August. As an overall feature, more precipitation is observed over the mountainous area to the west and north of the plain, corresponding to the orographic effect on the formation of afternoon showers (Kuwagata 1997). In addition,
there is a bulge of contour lines toward the Tokyo urban area, implying the presence of positive anomaly. In order to evaluate the spatial anomaly in Tokyo, a quadratic function was applied to interpolate the precipitation at surrounding 19 stations, shown in blue dots in Fig. 4, using a least-squares condition

$$\sum_{i} (P_i - (P^* + ax_i + by_i + cx_i^2 + dy_i^2 + ex_i y_i))^2 \rightarrow \min.$$  (2)

where $P_i$ is precipitation at station $i$ ($i = 1-19$), and $x_i$ and $y_i$ are eastward and northward distances from the target station, namely, Otemachi, Nerima, or Setagaya. The spatial anomaly was defined by $Q = (P_i - (P^*) - 1$, where $P_i$ is precipitation at the target station, and "( )" indicates the sum over all the NPP cases in the 30 years. It is to be noted that $Q$ satisfies the least-squares condition

$$\sum_{n} \left( \frac{(P_i(n))}{\sqrt{(P^*(n))}} - (Q + 1)\sqrt{(P^*(n))} \right)^2 \rightarrow \min.$$  (3)

where $(P_i(n))$ and $(P^*(n))$ are the sum over cases in the year $n$. By using (3), it was possible to evaluate the statistical significance of $Q$.

Figure 5 shows the values of $Q$ at the three stations for each time of the day and season, obtained by applying (2) and (3) for each six-hour period for three consecutive months. Otemachi is characterized by a distinct positive anomaly of 30% or more in the evening of the warm season, partly significant at the 5% level. Nerima and Setagaya also show positive anomaly from afternoon to evening of summer, although significance is weak.

For comparison, the result for all cases is shown in Fig. 6. The anomaly is much weaker than that for NPP cases, although a large area of statistical significance implies slightly inhomogeneous precipitation distribution that may be due to topographic effects. In other words, spatial anomaly of precipitation in Tokyo is most conspicuous for NPP cases from afternoon to early evening of the warm season, just as for the long-term trend.

4. Concluding remarks

By using hourly data for 118 years in the central part of Tokyo, and AMeDAS data for 30 years, precipitation in “no preceding precipitation” (NPP) cases was found to have both a positive trend and positive spatial anomaly in Tokyo from afternoon to early evening of the warm season. These results agree with our understanding that thermal and dynamical forcing of the urban heat island is strongest in the daytime of the warm season. The close similarity between long-term change (Fig. 2) and spatial anomaly (Fig. 5) adds to the plausibility of the urban heat-island effect as their cause. At the same time, the only weak trend for all cases is consistent with some previous results that an urban signal for Tokyo was not obvious in time-series analysis of precipitation (e.g., Kanae et al. 2004). In this respect, our results imply the limitation of urban influence, which is real but confined to a situation of enhanced heat island in the afternoon of the warm season.

A remaining problem is the spatial scale of urban influence on precipitation. It is believed that the warm-season daytime heat island of the Tokyo metropolitan area covers a large region spreading for several tens to a hundred kilometers, with a convergence zone far inland (Kimura and Takahashi 1991; Kusaka et al. 2000; Fujibe 2003). This situation implies the possibility that
urban-induced precipitation anomaly is found not only in the central part of Tokyo but over a much larger area extending inland. Further studies, including numerical simulations, will be needed to investigate such possibility.

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Comments and supplements

Results of supplementary analyses are described in the Supplement 1.

References

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