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LONG-TERM CHANGE AND SPATIAL ANOMALY OF WARM SEASON AFTERNOON PRECIPITATION IN TOKYO

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1. Introduction

The Tokyo metropolitan area is characterized by a high degree of urbanization, with a conspicuous heat island. 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. 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.

However, urban signals for precipitation are less distinct, apart from some indication of spatial anomaly of precipitation amount and local enhancement of convective systems (Sato et al. 2006). Indeed, 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. Although severe convective storms occasionally cause heavy rainfall in Tokyo, amounting to 100mm/h in some cases (Seko et al. 2007), it requires convincing evidence to establish the causal relationship between urban heating and precipitation.

There have been a number of studies indicating the increase of intense precipitation in Tokyo based on time series data (Yonetani 1982; Sato and Takahashi 2000). However, the rate of change is highly dependent on data periods and months, sometimes with inconsistent results (e.g., Yonetani 1989). The analysis of Kanae et al. (2004) for hourly data over 110 years (1890-1999) has revealed the dominance of multi-decadal variation, rather than a linear increase, in the frequency of heavy precipitation events in Tokyo. Recent studies have shown that increase of intense precipitation is a nation-wide feature (Fujibe et al. 2005, 2006), 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, as well as to examine the consistency between spatial anomaly and long-term changes.

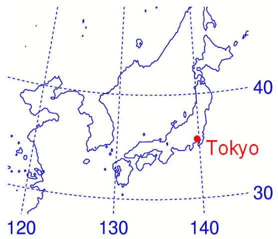

Fig.1 Map of East Asia. A detailed map of the Tokyo Metropolitan area is shown in Fig.5.

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 present study is based on this data set, to investigate the long-term change of precipitation at Tokyo. At the same time, 30-year data on the network of AMeDAS (Automated Meteorological Data Acquisition System), having a horizontal resolution of 15-20km, were used to capture the spatial anomaly of precipitation in the Tokyo area. By selecting cases that were not preceded by precipitation, we try to capture urban signals which are expected to be enhanced by daytime heating at urban surfaces.

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. For 1953 to 1955, data from 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

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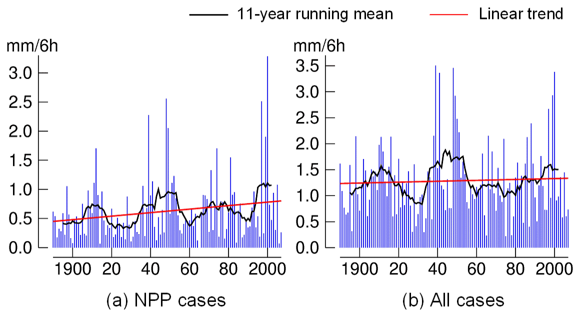

Fig.2 Six-hourly precipitation amount at Tokyo for 1700-2300 JST from June to August, averaged for "no preceding precipitation" (NPP) cases and all the cases. Each vertical bar (blue) indicates the value for each year.

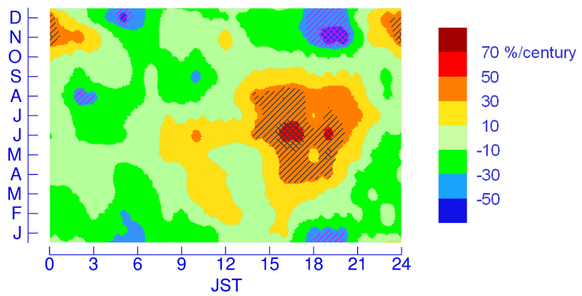

Fig.3 Linear trend *B*/*A* for each time of the day and month for NPP cases. Hatching and double hatching indicate the regions where the trend is significant at the 5% and 1% levels, respectively.

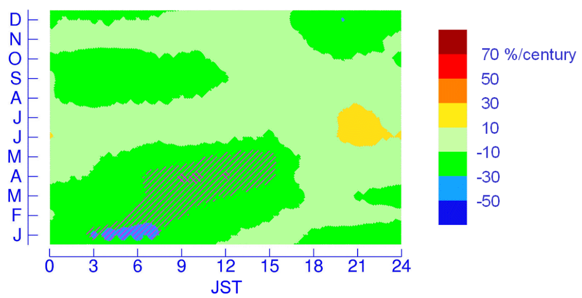

Fig.4 Same as Fig.3, but for all the cases.

1965.

The observation site is at Otemachi, in the central part of the city, after it moved by about 600m eastward in 1923. The resolution of observation changed from 0.1mm to 0.5mm in October 1964, as the traditional raingauge was replaced by the tipping-bucket one, although the former was used again from 1966 to 1967 to measure the precipitation below 0.5mm. For the period from 1975 to 1988, data are recorded at a 1mm 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 1mm resolution, on the assumption of no evaporation from the tipping bucket.

As suggested so far, urban induced precipitation is most likely to develop in the afternoon of the warm season, as the heat-island circulation is enhanced in the presence of solar heating. In order to represent this type of precipitation, "no preceding precipitation" (NPP) cases were defined as not preceded by precipitation of ≥1mm for the last six hours. For each time of the day and season, the mean precipitation intensity for year *n*, *P*(*n*), was obtained by averaging six-hourly precipitation amount over NPP cases.

2.2 Results

Figure 2a shows the time series of NPP precipitation for 1700 to 2300 JST for the three months June to August at Tokyo, based on the no evaporation assumption. There are considerable year-to-year variations, but the overall feature has an increasing trend. The linear trend was obtained using the least-squares fitting

$$\sum_n [P(n) - \{A + B\,(n - \frac{n_1+n_2}{2})\}]^2 \rightarrow \text{min.}, \qquad (1)$$

where $P(n)$ is six-hourly precipitation averaged over NPP cases in the year n, 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.

Figure 3 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 in late afternoon to early evening of the warm season.

For the sake of comparison, the result for all the cases is shown in Figs.2b and 4. The trend is much weaker (~10%/century at most) than for NPP cases. Thus the increase of precipitation at central Tokyo is characteristic to NPP cases in the afternoon of the warm season.

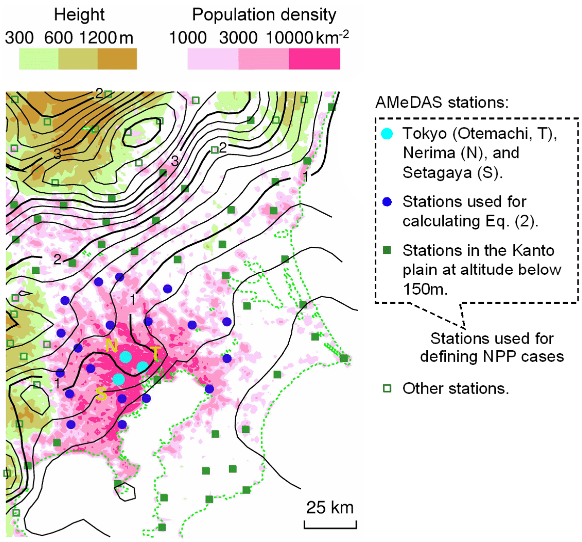

Fig.5 Distribution of six-hourly precipitation amount for NPP cases for 1700-2300 JST from June to August. Contour intervals are 0.25mm/6h.

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 the area surrounding Tokyo, to 2007. Three stations, Otemachi, Nerima, and Setagaya, are located in the highly urbanized area of Tokyo. 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 1mm or more was observed during the preceding six hours over the Kanto plain, where data at 62 stations were available at altitude below 150m. A NPP case requires that the percentage of such stations should be less than 10%.

Figure 5 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, using a least-squares condition

$$\sum_i \{P_i - (P^* + ax_i + by_i + cx_i^2 + dy_i^2 + ex_iy_i)\}^2 \rightarrow \min., \quad (2)$$

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 $Q = \langle P_0\rangle / \langle P^*\rangle - 1$, where P_0 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

$$\sum_n \left(\frac{\langle P_0(n)\rangle}{\sqrt{\langle P^*(n)\rangle}} - (Q+1)\sqrt{\langle P^*(n)\rangle}\right)^2 \rightarrow \min., \quad (3)$$

where $\langle P_0(n)\rangle$ and $\langle P^*(n)\rangle$ are the sum over cases in the year n. By using (3), it was possible to evaluate the statistical significance of Q. In the same way, the anomaly at Nerima and Setagaya was calculated.

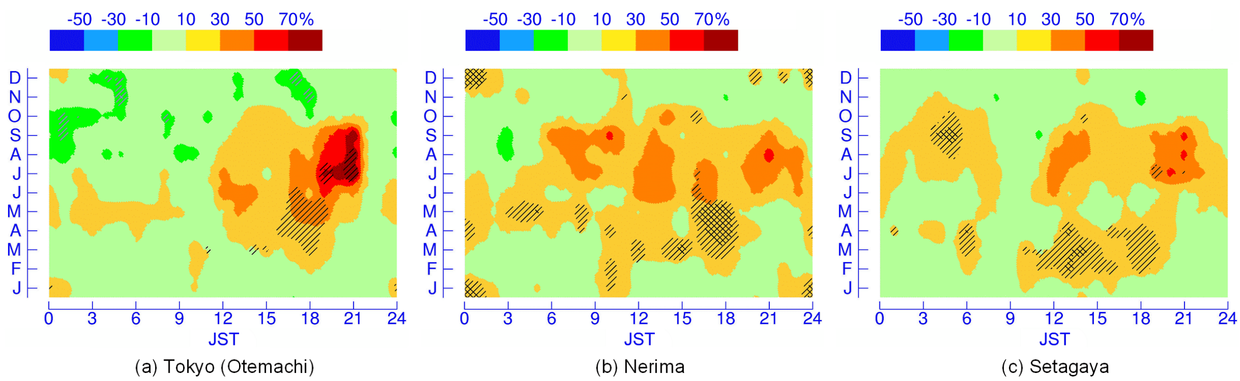

Fig.6 Spatial anomaly Q for each time of the day and month for NPP cases. Hatching and double hatching indicate the regions where the anomaly is significant at the 5% and 1% levels, respectively.

Figure 6 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 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 the result for all cases (not shown) the anomaly in Tokyo is much weaker than that for NPP cases. In other words, spatial anomaly of precipitation in Tokyo is most conspicuous for NPP cases from afternoon to early evening of the warm season.

4. Concluding remarks

By using hourly data for 118 years at the center of Tokyo, and AMeDAS data for 30 years, positive signals of precipitation at Tokyo have been detected for both long-term precipitation change and spatial anomaly. The signals are most conspicuous for “no preceding precipitation” (NPP) cases from afternoon to early evening of the warm season, in consistent with our understanding that thermal and dynamical forcing of the urban heat island is strongest in the daytime of summer. The close similarity between long-term change (Fig.3) and spatial anomaly (Fig.6) adds to the plausibility of urban effects as their cause. At the same time, the only weak trend for the all cases is consistent with some previous results that an urban signal was not obvious in time-series analysis of precipitation at Tokyo (e.g., Kanae et al. 2004).

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 wide region spreading for several tens to a hundred kilometers, with a convergence zone far inland of Tokyo (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 wider area extending inland. Further studies, including numerical simulations, will be needed to investigate such possibility.

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