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REGIONAL CHARACTERISTICS OF DIURNAL VARIATION OF LOCALIZED HEAVY RAINFALL FREQUENCY IN TOKYO AND ITS SURROUNDINGS

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Abstract The present study aimed to clarify the regional characteristics of the diurnal variation of localized heavy rainfall frequency in the Tokyo metropolitan area and Saitama Prefecture based on the dense hourly rainfall data acquired from 290 stations across summers of 15 years between 1994–2010 (June to September). The obtained results can be summarized as follows. The central to western parts of Saitama Prefecture (Cluster 2) displayed a single peak with a large maximum from the evening till the early night hours. In comparison, the western and southern parts of the Tama region (Cluster 4) and the western Tokyo area (Cluster 5) indicated a bimodal pattern with two peaks during the day and night. Moreover, central Tokyo, the northern Tama region, and southeastern Saitama Prefecture (Cluster 3) are located between these areas and can be considered a transition zone between the single-peak and bimodal areas. Despite the moderate increase in the frequency of heavy rainfall from evening to night in the eastern part of the Tokyo metropolitan area as well as the Saitama Prefecture (Cluster 1), it did not exhibit a clear maximum.

Keywords: localized heavy rainfall, diurnal variation, regional division, Tokyo metropolitan area

1. Introduction

In the mountainous region of the Kanto district, the rainfall frequency typically increases in the afternoon, whereas in the plain area, the rainfall frequency peaks are delayed (Saitoh and Kimura 1998). Concerning the diurnal variation of occurrence of heavy rainfall in the Tokyo metropolitan area, the amount and frequency of rainfall increases from noon till evening across the central Tokyo to Yamanote area (Fujibe 1998). Historically, from afternoon to early evening during summer, the rainfall amount has tended to increase beyond 30% per century (Fujibe *et al.* 2009), and the delays in rainfall over central Tokyo have increased (Sawada 2017). Sato *et al.* (2006) reported that several rainfall systems occurring in the mountainous regions during the day migrated eastward. The rainfall frequency is remarkably higher in the urban area than in the surrounding area.

To date, numerous studies related to the diurnal variation of rainfall have been conducted. Prior survey on inland areas reported frequent heavy rainfall from day to evening and at early hours of the night (Wallace 1975; Riley *et al.* 1987; Landin and Bosart 1989; Oki and Musiake 1994).

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Conversely, heavy rainfall in coastal regions occurs predominantly in the morning (Kousky 1980) and over the sea at midnight (Kraus 1963). Indicatively, factors regulating the diurnal variation of rainfall include the occurrence and development of systems which results in heavy rainfall, the location of its occurrence and migration, and the effect attributed to urban areas that induces the rainfall (Sato *et al.* 2006). Furthermore, the diurnal variation of heavy rainfall is influenced by the water vapor content in the local circulation, as well as by the diurnal variation of precipitable water, transportation of water vapor, convergence of the winds, and diurnal variation of the stability (Kimura *et al.* 1997; Kuwagata 1997; Saitoh and Kimura 1998; Iwasaki and Miki 2001; Sasaki and Kimura 2001; Iwasaki and Miki 2002). However, the number of sample cases in several statistical analyses was inadequate, and the majority of these studies collected rainfall data from the Automated Meteorological Data Acquisition System (AMeDAS) and meteorological observatories of the Japan Meteorological Agency (JMA), which cover a spatial density of one observation station per 17 km^2. Thus, there is concern that localized heavy rainfall from a convective system within the ~10-km-scale was not adequately captured. Therefore, a more densely distributed rain-gauge network data should be utilized considering the spatial scale of the rainfall area for statistically investigating localized heavy rainfall frequency.

In the present study, we conducted advanced analyses by including rainfall data from Saitama Prefecture against Takahashi *et al.* (2016), which used the rain-gauge data from multiple data sources and investigated the diurnal variation of heavy rainfall frequency as preliminary research. The present study targeted the localized heavy rainfall, that was classified based on Oka *et al.* (2019), which focused on the spatial extent of the rainfall area, and classified the heavy rainfall areas into *localized heavy rainfall area* and *heavy rainfall area with widespread rainfall* in the Tokyo metropolitan and Saitama Prefecture. The present study aims to clarify the regional characteristics of the diurnal variation in the frequency of localized heavy rainfall over Tokyo metropolitan area and Saitama Prefecture.

2. Data and Quality Check

The Tokyo metropolitan area and Saitama Prefecture were considered the overall study area (35.5–36.25°N, 138.875–140.0°E; Fig. 1a). In total, we acquired hourly rainfall data from 290 observation stations (Fig. 1b) as follows: from AMeDAS and the meteorological observatory of the JMA (35 stations), the Ministry of Land, Infrastructure Transport, and Tourism (i.e., MLIT, 59 stations), the East Japan Railway Company (i.e., JR EAST, 49 stations), the Tokyo Metropolitan Government Bureau of Construction (i.e., Tokyo Metropolis, 109 stations), and the River and Erosion Control Division of the Department of Land Development of the Saitama Prefecture (i.e., Saitama Prefecture, 38 stations). The analysis period included summers of 15 years (June to September) from 1994 to 2010, excluding 1997 and 2006, for which the rainfall data in the Saitama Prefecture were unavailable. As the spatial density of the rainfall observation station is approximately one station per 5.4 km^2, it can appropriately capture the extreme localized heavy rainfall in the evening with a cumulonimbus scale smaller than 10-km. As the rainfall data is recorded at a resolution of 1 or 0.5 mm by AMeDAS and the meteorological observatory, 0.1 or 0.5 mm by the Ministry of Land, Infrastructure Transport, and Tourism, and 1 mm by the East Japan Railway Company, Tokyo metropolis, and Saitama Prefecture, we unified the rainfall data resolution of all stations with a 1 mm unit for the current analysis. Moreover, the rainfall data were approximated to the nearest unit digit, following Oka *et al.* (2019). Furthermore, the rainfall data were subjected to intensive quality checks by the following methods:

(1) If the observation station was relocated more than 5 km horizontally or 50 m vertically during the target period, the station was excluded from the analysis data (JMA 2021).

(2) If the rainfall amount was more than 140 mm/h, it was regarded as an anomalous value and excluded (Takahashi *et al.* 2011).

(3) A rainfall distribution map was drawn if a rainfall of 20 mm/h or more was observed at a station. In the case of no rainfall being recorded at the neighboring stations, the reading from this isolated station was excluded (Takahashi *et al.* 2011).

(4) The rainfall data indicates 0 mm/h as missing data if more than three stations situated within 5 km observed a precipitation of 10 mm/h or more (Takahashi *et al.* 2011).

(5) The 15-year-average of total summer rainfall amounts from the rainfall observation stations were compared with the mesh climate value reported by the JMA. Based on this comparison, any observation displaying a large variation between the average rainfall amounts and the mesh climate value was excluded (Oka *et al.* 2019).

Based on this process, we considered the data from 290 observation stations that contained less than 15% missing data.

In this study, rainfall greater than 20 mm/h is defined as "heavy rainfall" (Fujibe *et al.* 2002; Nakanishi and Hara 2003; Takahashi *et al.* 2011; Oka *et al.* 2019), and a given day is regarded as a "heavy rainfall day" if heavy rainfall was observed at more than one station. As such, if the number of stations observing more than 5 mm/h rainfall was less than 60% of all stations, the given day was defined as a "localized heavy rainfall day" (Oka *et al.* 2019), which forms the target scope of this study. Hereinafter, the localized heavy rainfall or the localized heavy rainfall day is expressed as "heavy rainfall" or "heavy rainfall day," respectively.

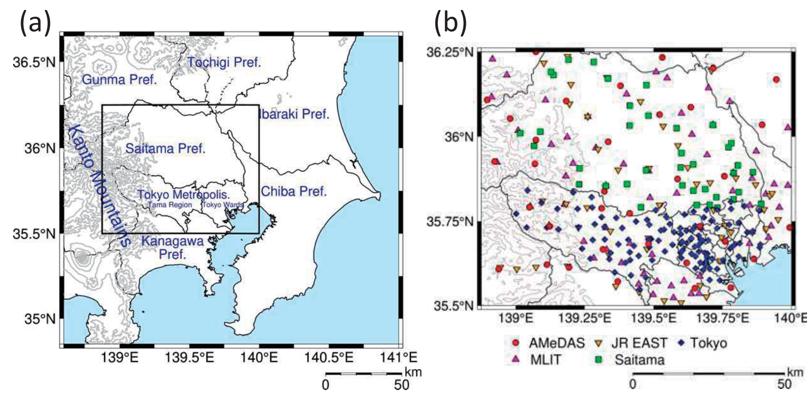

Fig. 1 (a) Present research area: Kanto region; (b) location of observation stations.
Black frame in (a) depicts analysis area of rainfall in (b).
In (b), MLIT is Ministry of Land, Infrastructure, Transport and Tourism.

3. Regional Classification based on Diurnal Variation of Localized Heavy Rainfall Frequency

To clarify the regional characteristics of the diurnal variation of heavy rainfall frequency, we initially determined the hourly frequency of heavy rainfall during the summer (June to September) for 15 years recorded at 290 stations. Thereafter, we categorized the diurnal variation of each station and segmented the area from the spatial distribution of the stations within the same category. Considering the similarity of diurnal variations for classifying the stations, the daily frequency of 24 instances of heavy rainfall per day at each observation station was standardized such that the average was 0 and the standard deviation was 1. Subsequently, the cluster analysis (Ward's method) was performed considering the Euclidean distance as a similarity index. In the merging process of clusters (Fig. 2), the distance index between the merging clusters discontinuously increased when the number of clusters reached five. Eventually, the diurnal variations of localized heavy rainfall frequency were categorized into five types (Fig. 3).

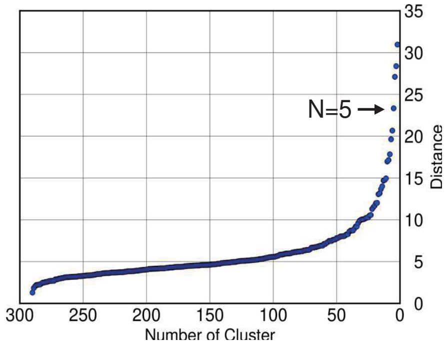

Fig. 2 Number of cluster and bond distance.

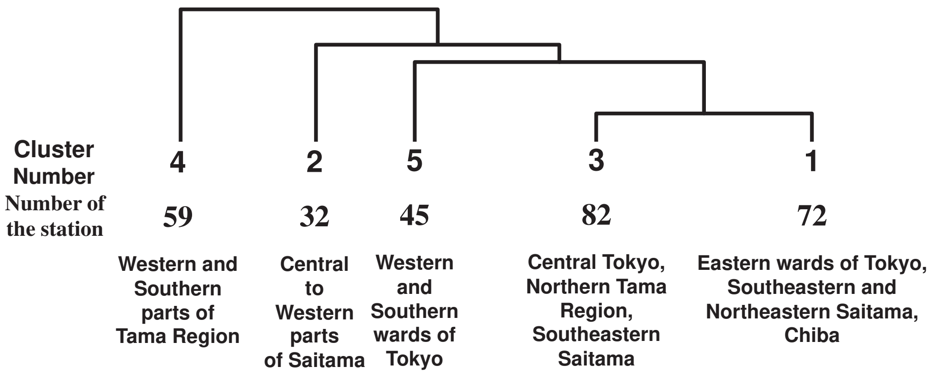

Fig. 3 Dendrogram derived from cluster analysis.

The regional division obtained by the stated procedure is depicted in Fig. 4, wherein the black boundary lines demarcate the cluster regions. Each area surrounded by black lines is defined as a "main region." According to Fig. 4, some stations existed in overlapping main regions. Where this occurred, the area with the most affiliated stations was marked as the main (cluster) region. Moreover, in some cases, the stations assigned to overlapping cluster number were located some distance away from the main region. In those case, the area was regarded as unique, even though it contained an equal number of clusters. The areas surrounded by red-dashed boundary lines were defined as "subareas" which the same cluster areas that are situated farther from the main regions

(Fig. 4). Upon calculating the diurnal variation of the heavy rainfall frequency in each cluster region, we considered the hourly heavy rainfall frequency data of the stations located in the main region. Notably, the data from the station in the subarea were excluded from the analysis. Furthermore, the red-dashed boundary lines overlapping the black boundary lines indicate the boundary of the subareas adjacent to that of various clusters in the main region.

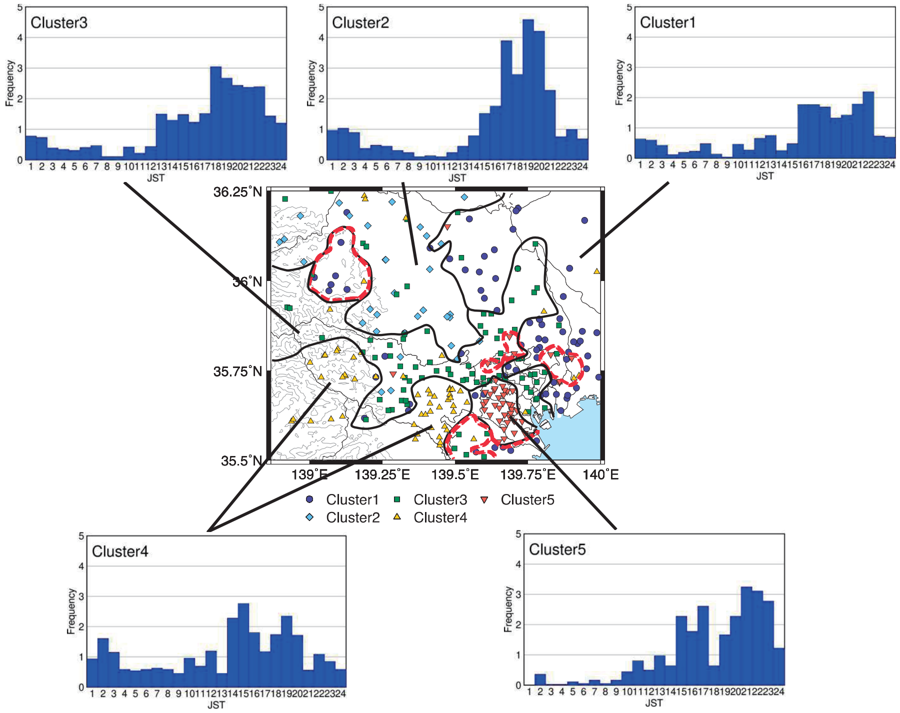

Fig. 4 Regional division by diurnal variation of hourly localized heavy rainfall frequency in summer (June to September), and diurnal variation of localized heavy rainfall frequency in each region. Black-solid lines indicate the boundary between various clusters in main region. Red-dashed lines indicate the boundary between the subarea (same cluster area but located farther from main region) and other regions.

Cluster 1 (72 stations) covers the area from the eastern wards of Tokyo to the southeastern and northeastern Saitama Prefecture and Chiba Prefecture, Cluster 2 (32 stations) spans the area of the central and western parts of Saitama Prefecture, Cluster 3 (82 stations) area is spread over central Tokyo, the northern Tama region, and southeastern Saitama Prefecture. In contrast, Cluster 4 (59 stations) and Cluster 5 (45 stations) enclosed the western and southern parts of the Tama region and the western and southern wards of Tokyo, respectively. Compared to other clusters, these clusters exhibited improved regional coherence.

4. Diurnal Variation Characteristics of Localized Heavy Rainfall Frequency in each Region

In this section, we discuss the characteristics of the diurnal variation of heavy rainfall in each region based on the cluster analysis. According to Fig. 4, the heavy rainfall frequency slightly increased from 16:00 till 22:00 JST, but its maximum was not large compared with that of other regions in Cluster 1. In Cluster 2, the heavy rainfall frequency had a large single maximum peak in effect from the evening to the early hours of night (17:00–21:00 JST) and the peak was remarkably higher than that of the remaining clusters. Subsequently, this is consistent with that of the inland area reported by a previous study (Sawada 2000). In contrast, the diurnal variations of heavy rainfall frequency in Clusters 4 and 5 exhibited a bimodal pattern with two peaks during day and night. More specifically, heavy rainfall frequency peaks emerged from 14:00 till 16:00 JST and 18:00 till 20:00 JST in Cluster 4, and from 15:00 till 17:00 JST and 20:00 till 23:00 JST in Cluster 5. Notably, the maximum of the frequency was more prominent in Cluster 5 than in Cluster 4. In the interval between these two peaks, the heavy rainfall frequency decreased after 17:00 JST in Cluster 4 and 18:00 JST in Cluster 5, and remarkably, it was extremely low at 18:00 JST in Cluster 5.

The heavy rainfall frequency in Cluster 3 increased in the afternoon, with the first peak between 13:00–17:00 JST and second peak lasting from 18:00 JST till 22:00 JST. Presumably, this area acts as a transition zone between the diurnal variation of the single peak in Cluster 2 (inland area) and the bimodal pattern in Clusters 4 and 5. The findings of a previous related study (e. g. Fujibe 1988; 1998; Sawada 2000; 2017) did not reveal the bimodal pattern or single-peak region in the diurnal variation of the heavy rainfall frequency over the surrounding regions of the Tokyo metropolitan area. Hence the present study is the first report of this, by utilizing the data of densely distributed observation stations.

Overall, the characteristics of the diurnal variation of heavy rainfall frequency in these areas revealed that the frequency peak of the heavy rainfall in the eastern region of the study area, *e.g.,* Clusters 1 and 5, occurred after a certain period from that in the western area, *e.g.*, Clusters 2 and 4. This result is consistent with the reports of Saitoh and Kimura (1998), signifying that the heavy rainfall frequency in the Kanto Plain increases later in the day. Therefore, as the bimodal pattern containing two peaks appears later in Cluster 5 than it does in Cluster 4, it can be stated that the rainfall system occurring in the Oku-Chichibu area possibly shifts toward the Kanto Plain at night (Saitoh and Kimura 1998; Sato *et al.* 2006). However, the diurnal variation of the bimodal pattern (two peaks during the day and night) cannot be explained based only on the precipitable water and rainfall migration in the Kanto district scale. Presumably, the diurnal variation of the wind systems which produce the wind convergence zone may also contribute to the occurrence of two peaks in the diurnal variation of heavy rainfall in and around the Tokyo metropolitan area.

5. Summary

In this study, cluster analysis was conducted based on the diurnal variation of heavy rainfall frequency at 290 meteorological stations over 15 summer seasons between 1994–2010 in Tokyo and its surrounding areas, with the analyzed area segmented into five regions. The present study reveals detailed regional characteristics of rainfall diurnal variation in the Tokyo metropolitan area and Saitama Prefecture. Heavy rainfall frequency did not exhibit a clear maximum in Cluster 1 which covers the area from the eastern ward of Tokyo to the southeastern and northeastern Saitama Prefecture and Chiba Prefecture. In Cluster 2 that spans the area of the central and western Saitama Prefecture, the heavy rainfall frequency exhibits a single peak with a large maximum value during the evening and at early hours of night. Contrarily, the western and southern regions of the Tama region in Cluster 4 and the western and southern wards of Tokyo in Cluster 5 displayed a bimodal pattern with two peaks during day and night, respectively. In central Tokyo, the northern Tama region, and southeastern Saitama Prefecture in Cluster 3, the diurnal variation of heavy rainfall frequency is regarded as a transition zone between Cluster 2 (single peak) and Clusters 4 and 5 (bimodal pattern with two peaks). Furthermore, the frequency peak of the heavy rainfall in the eastern region of study area occurs after a certain period from the in the western area later in the day. This corresponds with previous research, indicating that a rainfall area occurs in the mountainous region and moves eastward. Thereafter, the result that the diurnal variation of the heavy rainfall reveals bimodal pattern and single-peak region in and around Tokyo metropolitan area was first clarified in the present study, by using the data of densely distributed observation stations.

However, the diurnal variation in a bimodal pattern with two peaks at day and night cannot be explained only based on the rainfall migration in the Kanto district scale. Possibly, the diurnal variation of the wind systems producing a converge zone of the winds contributes to the bimodal pattern of two peaks in and around the Tokyo metropolitan area. Therefore, the wind system related the localized circulation must be investigated by a complementary analysis. In future, we intend to focus on the western wards of Tokyo (Cluster 5) and reveal the relationships between the rainfall system with two-peak bimodal pattern of the localized heavy rainfall frequency and the localized wind systems, which is a factor contributing to occurrence and area of rainfall.

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(*: in Japanese, **: in Japanese with English abstract)