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RAINFALL CHARACTERISTICS AT THE INSTITUTE FOR NATURE STUDY, TOKYO AND THEIR INTERANNUAL VARIABILITY

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Abstract Rainfall characteristics and their interannual variability at the Institute for Nature Study, located in central Tokyo, were investigated using hourly and daily rainfall data, mainly from July 1990 to August 2021. Large interannual variabilities in monthly rainfall and the number of rainy days were found in October and July, respectively. Meanwhile, higher frequencies of heavy (≥5 mm/h and ≥10 mm/h) and light rainfalls (≥1 mm/h and <5 mm/h) were observed in October and June, respectively. Additionally, from the viewpoint of long-term change, the ratios of October rainfall and daily maximum rainfall in October to the annual rainfall tended to increase since around 2001. We suggest that the rainfall contribution caused by typhoons in October to the annual rainfall increased and was closely connected to the larger mean rainfall intensity in October since around 2001.

Keywords: rainfall characteristics, interannual variability, Institute for Nature Study

1. Introduction

The Institute for Nature Study (INS), located at Minato Ward of Tokyo, Japan is an urban green area that contrasts with the center of Tokyo, which is densely covered with artificial land structures (Fig. 1). Since the late 1960s, micrometeorological observations have been intermittently conducted at INS to examine the characteristics of the natural environment and their changes (e.g., Sugawara *et al*. 1969). Sugawara (2001) studied the secular changes in climatic factors at INS using those mean values every 10 years for 1971–2000. They reported that INS had moderate climate change, except for rainfall, compared with the urbanized areas in Tokyo. They also described that understanding the tendency of rainfall variability based on the mean values for the 10 years was difficult as rainfall had large temporal variability. Moreover, some earlier studies (e.g., Akasaka *et al*. 2018) have examined rainfall characteristics at INS in more detail using daily and hourly rainfall data since 1990 and 2014, respectively.

On another note, some earlier studies pointed out that the short-time heavy rainfall frequency around Tokyo tended to increase in the afternoon during the warm season (e.g., Fujibe *et al*. 2009). Nowadays, measures have been taken at INS to prevent surface soil erosion during the rainy season. Although the Tokyo surface observation site of the Japan Meteorological Agency (JMA) is located 6.5 km north of INS, the spatial representativeness of rainfall, especially

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short-time rainfall, is lower than those of other meteorological elements. Clarifying local rainfall characteristics using rainfall data observed in situ is vital as rainfall has large temporal and spatial variabilities. Thus, this study aims to clarify rainfall characteristics and their changes at INS using hourly and daily rainfall observed at INS, mainly from July 1990 to August 2021.

2. Data and Methodology

In this study, the primary data source was daily and 10-min rainfall data at INS, observed by the tipping bucket rain gauge with resolution of 0.5 mm. The daily rainfall data from 1968 to 1972 and from July 1990 to June 2011 were the same as those in Akasaka *et al*. (2020) and Akasaka *et al*. (2018), respectively. Although the locations of the observation site during 1968–1972 and since 1990 were slightly different, both locations were within INS. There were continuous missing values for April 2007 and October–November 2008 and 2010. The 10-min rainfall data between January 2014 and December 2019 were the same as those in Akasaka *et al*. (2020). New data added in this study include those from January 2020 to August 2021. These also include missing values for March–June 2014, June 2015–June 2016, and August to October 2020. A rain gauge was installed near the front gate of INS (Fig. 1).

On the basis of these rainfall data, hourly, monthly, and annual rainfalls were calculated when missing values were less than 20% for each hour, month, and year, respectively. We also used hourly, monthly, and annual rainfalls at the Tokyo observation station, provided by JMA (hereafter Tokyo JMA station) for the same period to compare and make up for rainfall characteristics and their variabilities at INS. According to Minematsu *et al*. (2016), Tokyo JMA station has been located around the north side of the Imperial Palace since 1882. Although the observation station had been located at Otemachi from 1964 to 2014, the location moved from Otemachi to the Kitanomaru Garden in December 2014. Therefore, the rainfalls before December 2014 and from December 2014–August 2021 were observed at Otemachi and the Kitanomaru Garden, respectively.

The number of rainy days and the mean rainfall intensity were calculated by counting the days when daily rainfall exceeded 0.5 mm and dividing the rainfall amount by the number of rainy days in each month and year, respectively, to analyze the rainfall characteristics at INS. Additionally, for investigating rainfall intensity, the number of hours and total rainfall amounts were calculated monthly by adding up hourly rainfall exceeding 5 and 10 mm to define indices of heavy rainfalls, and the maximum daily rainfall was determined for each month. An index of weak rainfall was also defined by the number of hours and total rainfall amount between 1 and 5 mm/h for each month.

3. Rainfall Characteristics at INS

Annual rainfall and number of rainy days at INS and Tokyo JMA station

The mean annual rainfall and number of rainy days averaged from 1991 to 2019 at INS were 1493.5 mm and about 114 days, respectively. The mean annual rainfall was 55 mm lower than that at Tokyo JMA station, whereas the mean annual number of rainy days was about the same as that at Tokyo JMA station. Lower annual rainfall amounts of less than 1500 mm were continuously shown at INS from the middle of the 1990s to the beginning of the 2000s (Fig. 2).

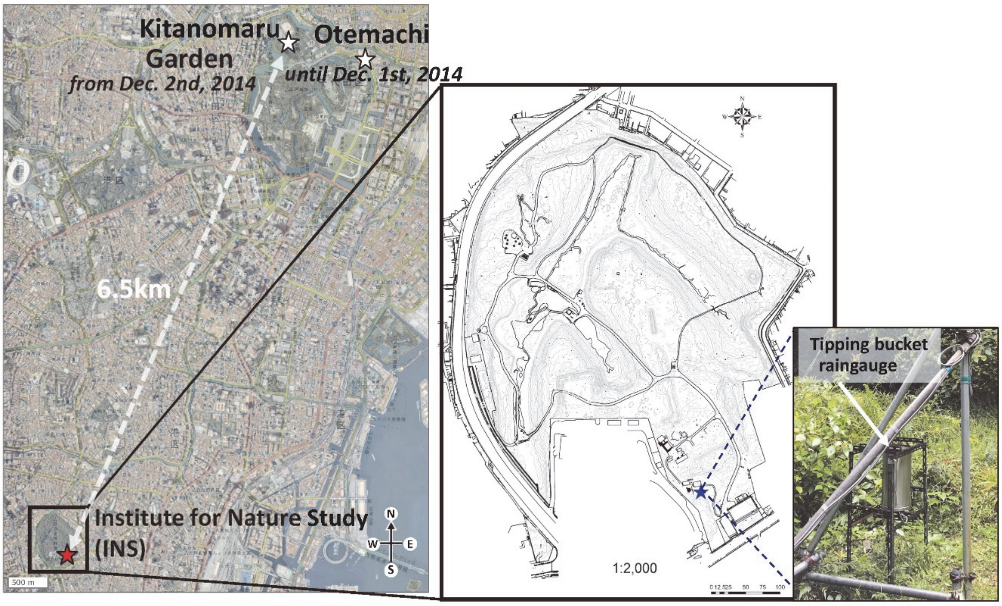

Fig. 1 Locations of meteorological observation site at the Institute for Nature Study (INS) installed in 2014 and Tokyo JMA station (Otemachi and the Kitanomaru Garden), and the photo of the rain gauge at INS. The left and central figures are based on topographic map and aerial photography published by the Geospatial Information Authority of Japan, respectively. Red and blue stars in the left and central figures indicate the locations of INS and the rain gauge at INS, respectively. Right figure indicates the photo of the rain gauge at INS.

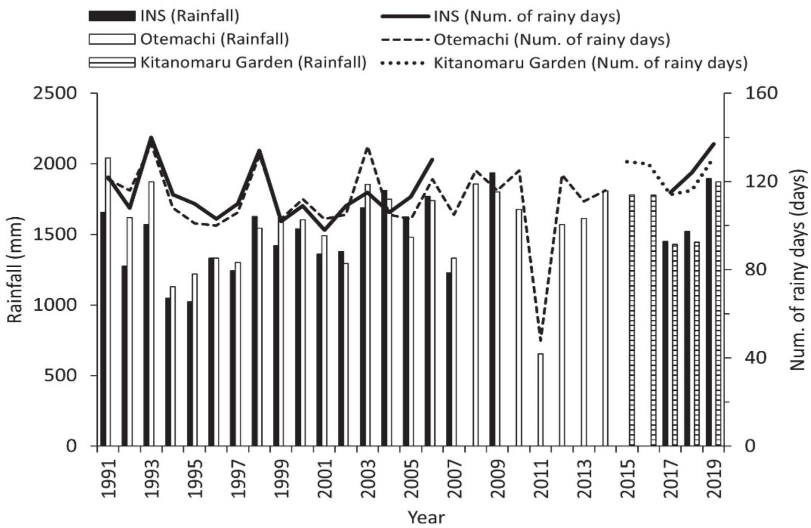

Fig. 2 Annual rainfall and number of rainy days at INS and Tokyo JMA station from 1991 to 2019

Monthly rainfall and number of rainy days at INS

Figures 3a and 3b indicate boxplots of monthly rainfall and the number of rainy days at INS for July 1990–August 2021, respectively. Higher mean monthly rainfalls of greater than 200 mm appeared from September to October due to the influences of typhoons and autumn rain fronts (Fig. 3a). Lower values (less than 100 mm) were shown from December to February due to the dry northwesterly wind. Larger differences between the mean values and the medians were shown in October. Furthermore, the highest monthly rainfall (812.0 mm) appeared in October 2004 when the centers of two typhoons passed around the Kanto Plain in which INS is located. These suggest that the high daily rainfalls caused by typhoons contribute to the larger interannual variability in monthly rainfall in October.

The higher mean monthly number of rainy days was shown in June and September (Fig. 3b). These periods correspond to the rainy season due to the influences of the *Baiu,* and autumn rain fronts and typhoons, respectively. Meanwhile, a larger interannual variability in the monthly numbers of rainy days was observed in July. The highest number (26 days) was shown in July 2020, when the withdrawal of the *Baiu* season occurred later than normal (around August 1 as shown by JMA 2021a). Thus, we suggest that the large interannual variability in the number of rainy days in July was closely related to the withdrawal of the *Baiu* season, which occurs around July 19 on average in the Kanto District (JMA 2021b).

The monthly mean rainfall intensities were higher in August and October (Fig. 3c). It is suggested that the highest value in October was brought by the large amount of daily rainfall due to typhoons. Whereas in August, the mean monthly rainfall showed almost the same value as that

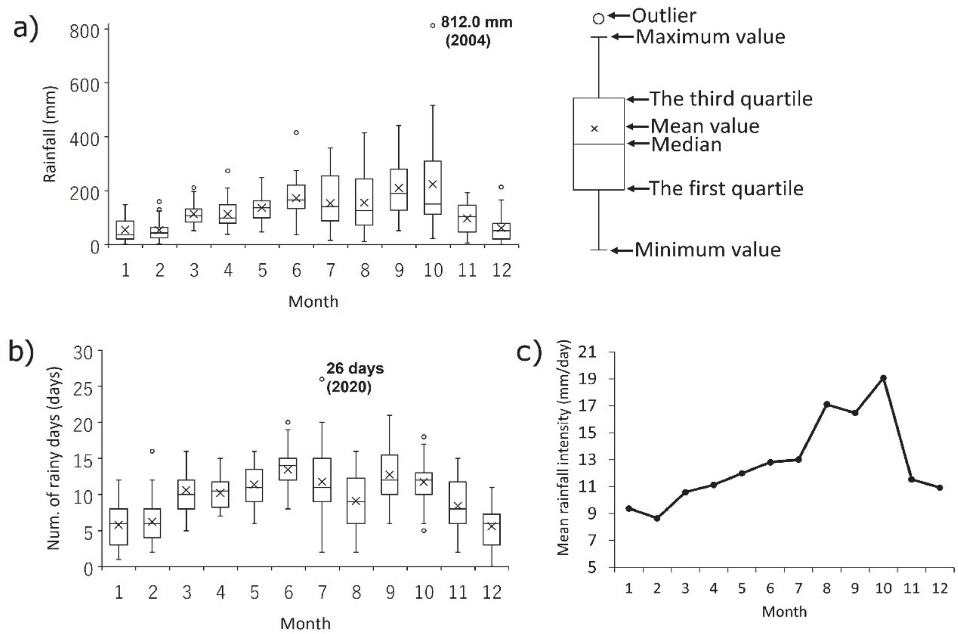

Fig. 3 Monthly rainfall, number of rainy days, and mean rainfall intensity at INS for July 1990–August 2021. (a) and (b) indicate boxplots of monthly rainfall and the number of rainy days, respectively. Legend of boxplot is shown in the upper right. Outliers indicated by circles in (a) and (b) mean values exceeding 1.5 times of the interquartile range in each month. (c) indicates the mean rainfall intensity.

in July (Fig. 3a) and the mean monthly number of rainy days was lower in the warm season (Fig. 3b). Therefore, the mean rainfall intensity increased in August than in other months in the warm season.

Seasonality of heavy and light rainfalls at INS

Figure 4 shows the seasonality of heavy and light rainfalls in hourly precipitation from January 2014 to August 2021. Both frequencies of heavy rainfalls exceeding 5 and 10 mm/h had larger values in October, especially for heavy rainfalls exceeding 5 mm/h (Fig. 4a). Subsequently, high frequencies of heavy rainfalls exceeding 5 mm/h appeared in June and August. Light rainfalls greater than or equal to 1 mm/h and less than 5 mm/h were most frequently observed in June (Fig. 4b). This means that both heavy and weak rainfalls were more frequently observed around Tokyo during the *Baiu* season. Also, high total amounts of heavy rainfalls were markedly shown from June to October (Fig. 4c).

For the study period, heavy rainfalls were observed to be seemingly frequent during the morning hours and 17–21 JST from June to September and regardless of time in October. Similar characteristics on the seasonality of heavy and light rainfalls were confirmed at Tokyo JMA station (Figure not shown). Kanai *et al*. (2019) showed lower correlation coefficients of 10-min rainfalls between INS and Tokyo JMA station from July to September than those in other months. Thus, investigating the simultaneity of hourly rainfalls in detail in future studies is necessary, especially heavy rainfalls between INS and Tokyo JMA station.

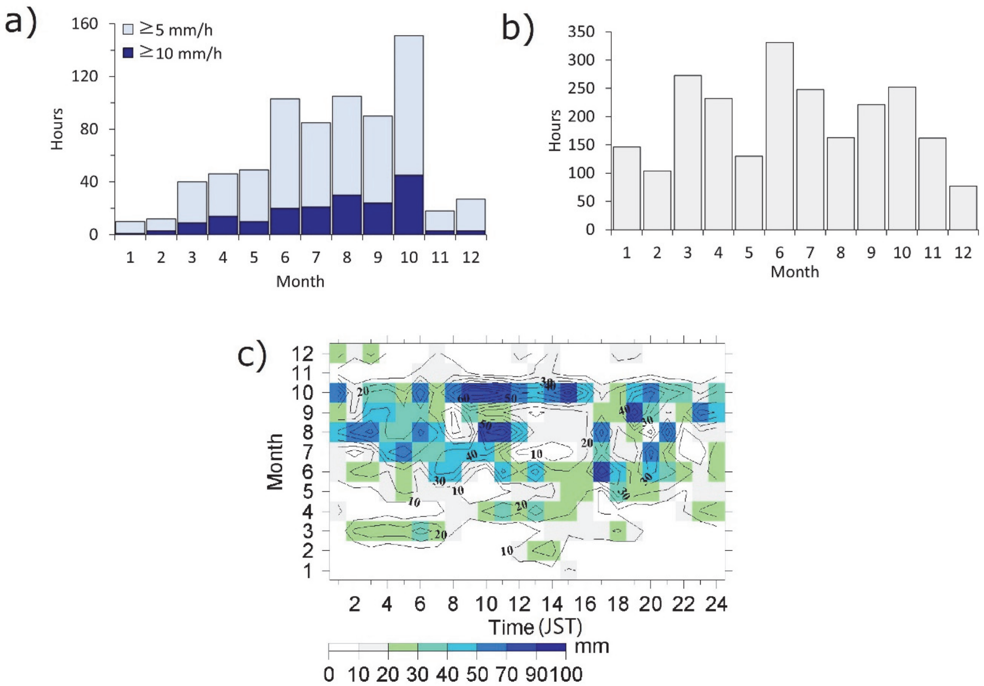

Fig. 4 Number of hours of heavy and light rainfalls (a and b) and total amount of heavy rainfall (c) at INS for January 2014–August 2021. (a) and (b) indicate heavy rainfall (≥5 mm/h and ≥10 mm/h) and light rainfall (≥1 mm/h and <5 mm/h), respectively. (c) indicates the cumulative heavy rainfall (≥5 mm/h) added up for the data period. The contour interval is 10 mm.

4. Interannual Variability in Rainfall Characteristics

Monthly rainfall, number of rainy days, and mean rainfall intensity since July 1990

October rainfall greater than 400 mm frequently appeared since 2004, although missing values were included since 2010 (Fig. 5a). Monthly rainfall from March to May more frequently exceeded 200 mm/month since 2007. Whereas the monthly numbers of rainy days were relatively lower (less than 10 days) during July–August before 2003, they tended to more frequently exceed 15 days since around 2003 (Fig. 5b). The mean rainfall intensity had relatively high values of greater than 20 mm/day from August to October since around 2001 (Fig. 5c). Mean rainfall intensities of greater than 30 mm/day appeared since 2001, especially in October. The high October rainfall of more than 300 mm frequently occurred since around the same time as shown in Fig. 5a, whereas the number of rainy days in October had no such increasing trend, as shown in Fig. 5b.

October rainfalls had larger interannual variations in rainfall amount than those of other months and tended to increase, as shown in Figs. 3a and 5. Thus, this study focused on the secular change in October rainfall in the next section.

Secular changes in monthly and maximum daily rainfall in October since 1968

We used October rainfall data at INS and Tokyo JMA station to examine longer-term change in October rainfall at INS because the secular changes in monthly rainfall amounts have similar tendencies for INS and Tokyo JMA station, as reported by Akasaka *et al.* (2018). Figure 6 indicates ratios of October rainfall and daily maximum rainfall in October to the annual rainfall

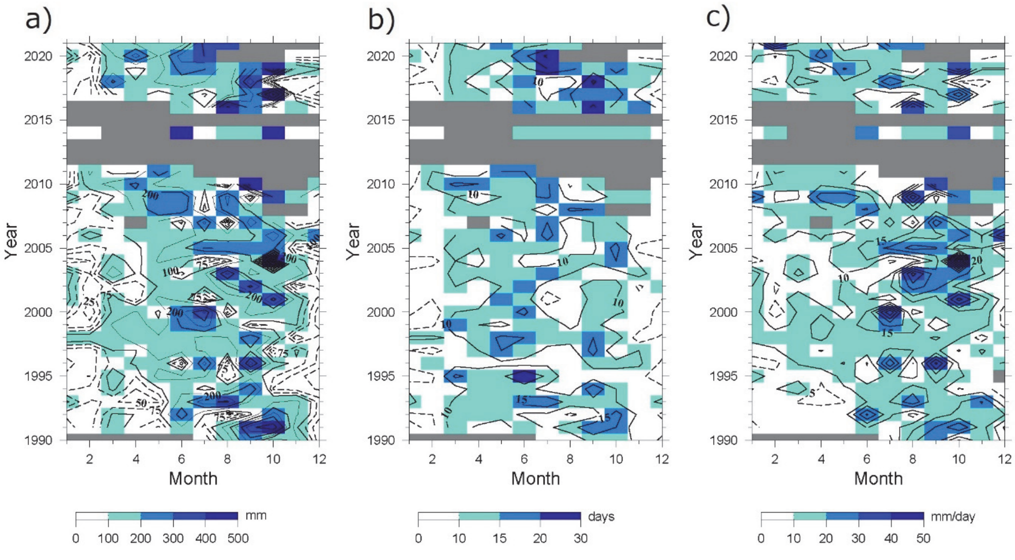

Fig. 5 Interannual variability in monthly rainfall (a), number of monthly rainy days (b), and mean monthly rainfall intensity (c) at INS from July 1990 to August 2021. Gray boxes indicate missing values. The contour interval is 25 mm below 100 mm with dashed line and is 50 mm above 100 mm with solid line in (a). The contour interval is 5 days above 5 days with solid line in (b). The contour of 5 days is shown by a dashed line. The contour interval is 5 mm/day above 10 mm/days with solid line in (c). The contour of 5 mm/day is shown by a dashed line.

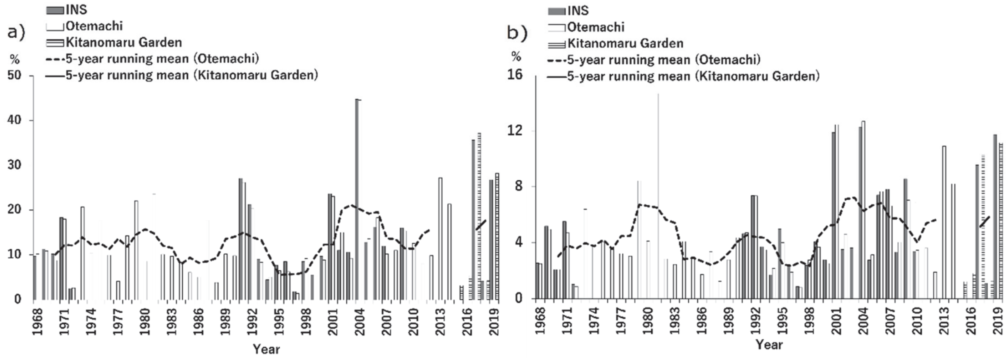

Fig. 6 Ratio of October rainfall (a) and daily maximum rainfall in October (b) to annual rainfall at INS and Tokyo JMA station from 1968 to 2019. Dashed line indicates the 5-year running mean at Tokyo JMA station (Otemachi and the Kitanomaru Garden).

at INS and Tokyo JMA station for 1968–2019. The ratio of October rainfall to the annual rainfall increased since around 2001 (Fig. 6a). The 5-year running mean of the ratio at Tokyo JMA station rose from 10–15% to 15–20% for the same period. Similarly, the ratio of daily maximum rainfall in October also increased since around 2001 (Fig. 6b). Akasaka *et al.* (2020) showed the top 6 daily maximum rainfall in October at INS and Tokyo JMA station for 1968–2019, although daily rainfall data at INS included continuous missing values. It was found that the same five cases of those at both stations were brought by typhoons since 2004. Thus, we suggest that daily rainfall amounts caused by typhoons had increasing trends at INS in October and that these significantly contributed to the frequent higher amounts of October rainfall since around 2001.

5. Conclusion

We examined the rainfall characteristics and their changes at INS, located in central Tokyo, on hourly, daily, monthly, and yearly basis, mainly from July 1990 to August 2021. From a climatology viewpoint, we found that higher monthly rainfalls and higher numbers of rainy days appeared in September–October and in June and September on average, respectively. Larger interannual variabilities in monthly rainfall and numbers of rainy days were shown in October and July, respectively. The largest mean rainfall intensity was shown in October, and the second largest one was shown in August. In the analyses using hourly rainfall data, higher frequencies of heavy and light rainfalls appeared in October and June, respectively.

From the perspective of these interannual variabilities, remarkable characteristics were shown in October rainfall characteristics; the ratios of October rainfall and daily maximum rainfall in October to the annual rainfall tended to increase since around 2001. Higher mean rainfall intensities in October also more frequently appeared during the same period. Also, this study suggests that rainfall amounts brought by typhoons tended to increase in October since around 2001.

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