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Relationships among Rainfall Distribution, Surface Wind, and Precipitable Water Vapor during Heavy Rainfall in Central Tokyo in Summer

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Abstract

The relationships between the occurrence of intense rainfall and the convergence of surface winds and water vapor concentration for typical heavy-rainfall cases were examined using data from July to August in 2011–2013 obtained from high-density meteorological observations in Tokyo, Japan. Additionally, the temporal variations in wind convergence and water vapor between days with and without heavy rainfall events were compared. Corresponding to the heavy-rainfall area, the convergence of surface winds tended to increase for several tens of minutes prior to the heavy rainfall. The peak of convergence was observed 10–30 min before the heavy rainfall occurrence, and convergence continued to increase for approximately 30 min until the convergence peak time. Around the heavy-rainfall area, the increase in the water vapor concentration index coincided with the increase in convergence. From these results, by monitoring the temporal variations and distributions of these parameters using a high-density observation network, it should be possible to predict the occurrence of heavy rainfall rapidly and accurately.

Keywords localized heavy rainfall; wind convergence; water vapor; high-density observation
1. Introduction

In recent years, short-term heavy-rainfall events that have caused various damages such as flooding and power outages due to lightning strikes have frequently occurred in the Tokyo Metropolitan area in summer. Fujibe et al. (2009) used hourly data for 118 years to demonstrate that precipitation in Tokyo during the afternoon and early evening of the warm season has an increasing trend. Takahashi et al. (2011) investigated the frequency distribution of heavy rainfall in the Tokyo Metropolitan area by using high-density hourly rainfall data and found that high-frequency areas of heavy rainfall are located in the northwestern part of the Tokyo Metropolitan area. Moreover, the lifetime of an individual cumulonimbus that causes heavy rainfall is usually less than one hour (Houze 1993). Thus, because thunderstorms on summer days develop locally and rapidly, predicting the location and time of heavy-rainfall occurrences is difficult. Several studies have pointed out that convergence of surface winds is observed prior to heavy rainfall. Fujibe et al. (2002) demonstrated that days with heavy rainfall in the Tokyo Metropolitan area tend to be characterized by both an “E-S-type” wind pattern, in which easterly and southerly winds converge in the vicinity of Tokyo, and higher humidity in the lower and middle troposphere. Nakanishi and Hara (2003) investigated the characteristics of local winds on days with intensification of rainfall in the Tokyo Metropolitan area and found that the enhancement of wind convergence occurred because of cold outflow. It has been suggested that occurrences of heavy rainfall can be predicted by monitoring the convergence of surface winds prior to heavy rainfall (Takahashi et al. 2009). In addition, the characteristics of the
water vapor field associated with thunderstorms on summer days have also been investigated (e.g., Yonetani et al. 1991; Iwasaki and Miki 2002). In particular, several studies have attempted to obtain information on water vapor using the Global Positioning System (GPS), which is a global navigation satellite system (GNSS) maintained by the United States (e.g., Sasaki and Kimura 2001; Inoue and Inoue 2007; Kusaka et al. 2010). Using signals from GPS satellites, precipitable water vapor (PWV) can be measured continuously and accurately. Niimura et al. (2000) showed that the PWV values derived from GPS and those from radiosonde observations are approximately consistent. They also determined that the probability of rainfall occurrence is high when PWV exceeds a threshold that is dependent on surface temperature, although this relationship is unclear for localized rainfall. Kanda et al. (2000) conducted a case study on thunderstorms in the Tokyo Metropolitan area to investigate the temporal and spatial relationships between GPS-derived PWV and rainfall intensity. They found that an increase in PWV can be observed 1 to 2 h before the occurrence of heavy rainfall. Thus, in view of the development process of cumulonimbus clouds, convergence of surface wind corresponding to the upward flow and the spatial concentration of water vapor are supposed to have taken place prior to the occurrence of heavy rainfall. By monitoring these features, the occurrence of heavy rainfall can be predicted. This study aims to clarify the evolutionary process of short-term heavy rainfall as a contribution to short-range forecasting of heavy rainfall that occurs locally. The relationships between the occurrence of heavy rainfall and the convergence of surface winds and water vapor concentration were examined using
high-density data obtained from meteorological observations in Tokyo.

2. Data and method

Detailed weather data obtained from automatic weather stations (Vaisala Weather Transmitter WXT510) installed at 30 stations such as Tokyo Metropolitan High School were used in this study. Data from the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency (JMA) and from rain gauges (98 stations) and air pollution monitoring systems (48 stations) of the Tokyo Metropolitan Government were also used. There were 138 rainfall observation points and 86 observation points of temperature and surface wind in the Tokyo Metropolis, excluding island areas (Fig. 1).

In this study, 10-min data for temperature, wind, and rainfall amount were used. The resolution of the rainfall observation differs according to data: either 1 mm or 0.5 mm for AMeDAS and rain gauges (tipping-bucket rain gauge) and 0.01 mm for the automatic weather stations (piezoelectric sensor). However, because we mainly focused on heavy-rainfall events, such as times with more than 5 mm of 10-min rainfall, we used the observed values without considering their differences. Before calculating the divergence of the surface winds, we interpolated the wind data into grid points with intervals of approximately 2.5 km using inverse distance weighted (IDW) interpolation with a 6-km search radius. The divergence values at each grid point were calculated using the centered difference:
where \( u \) and \( v \) are the velocity components at each grid point; \( \Delta x \) and \( \Delta y \) are the distances between the grid points in the east–west and north–south directions, respectively; and \( i \) and \( j \) are the grid numbers of the respective distances. Five-minute PWV and the water vapor concentration (WVC) index obtained from the GPS analysis were used as indices of the amount of water vapor. These data were derived from GNSS Earth Observation Network stations of the Geospatial Information Authority of Japan and campaign stations set up with the support of the Tokyo Metropolitan Area Convection Study for Extreme Weather Resilient Cities, as described by Shoji (2013). PWV is calculated from tropospheric delay of signals from GPS satellites and corresponds to the total atmospheric water vapor contained in a vertical column to the top of the atmosphere from the ground. In addition, Shoji (2013) proposed the “WVC index,” which expresses the degree of divergence and convergence of water vapor in the lower troposphere centered at the scale height of the horizontal gradient of water vapor. The horizontal gradient of PWV (\( \nabla \text{PWV}_G \)) can be estimated from the atmospheric delay gradient parameter \( G \). The WVC index represents the convergence of \( \nabla \text{PWV}_G \). Here the atmospheric gradient (\( G \)) is barely affected by the horizontal gradient near the lowest part of the atmosphere; instead, it is affected much more by the horizontal gradient at a height near the scale height (Shoji 2013). Therefore, the WVC index represents the spatial concentration of water vapor at 2 to 3 km above the ground, which corresponds to the upward flow.
The data used were from the time periods of July to August in 2011–2013. The total number of days in this period is 186 days. We focused on cases of heavy rainfall that occurred in a square domain measuring approximately 30 km on each side centered on the Tokyo Metropolitan area because high-density wind observations are required for the calculation of divergence. Heavy-rainfall days were defined as those in which more than 5 mm of 10-min rainfall was observed at 1010–2200 Japan standard time (JST) at any observation point in the Tokyo Metropolitan area. There were 71 rainfall observation points that were continuously operated during the period in the Tokyo Metropolitan area. The target time was determined taking into account the use of upper-air observations at 0900 JST for prediction. Using this criterion, 34 days were selected as heavy-rainfall days and the remaining 152 days were identified as no-heavy-rainfall days. Table 1 shows the selected heavy-rainfall days and the occurrence time of the daily maximum 10-min rainfall.

Besides the convergence of surface winds, unstable atmospheric conditions are an important factor in heavy-rainfall occurrence. Though there are many indices of atmospheric stability, several studies have pointed out that the Showalter Stability Index (SSI) and K-index, which represent the atmospheric stability and humidity in the lower to middle layer, show a good association with the occurrence of thunderstorms (Fujibe et al. 2002; Taguchi et al. 2002). Therefore, to examine the differences in the atmospheric features between heavy-rainfall days and no-heavy-rainfall days, daily SSI, K-index, and convective available potential energy (CAPE) calculated from upper-air
observation data at Tateno, provided by the University of Wyoming website (http://weather.uwyo.edu/upperair/), were used. The location of Tateno is shown in Fig. 1. The values of SSI, K-index, and CAPE were calculated as follows:

\[ SSI = T_{500} - T_L \]  
\[ KI = T_{850} - T_{500} + D_{850} - \left( T_{700} - D_{700} \right) \]  
\[ CAPE = g \int_{LFC}^{LNB} \frac{T_p - T}{T} \, dz \]

where \( T_{850}, T_{700}, \) and \( T_{500} \) are the temperature at 850, 700, and 500 hPa, respectively; \( D_{850} \) and \( D_{700} \) are the dew point temperature at 850 and 700 hPa, respectively; \( T_L \) and \( T_P \) are the temperature of a parcel lifted from 850 to 500 hPa and a parcel lifted from lowest of the atmosphere, dry-adiabatically to saturation and moist-adiabatically above that, respectively; \( T \) is the temperature of environment; \( LNB \) is the level of neutral buoyancy; \( LFC \) is the level of free convection; and \( g \) is the acceleration of gravity. In addition, the relationships between rainfall distribution and the convergence of surface winds and water vapor distributions for a typical heavy-rainfall case were examined. We also assessed the differences in the temporal variation in wind convergence and water vapor between heavy-rainfall days and no-heavy-rainfall days.

3. Results and discussion

3.1 Characteristics of atmospheric stability on heavy-rainfall days

Table 2 shows the percentile values of SSI, K-index, and CAPE at 0900 JST on the heavy-rainfall
days and the no-heavy-rainfall days. The SSI values are arranged in descending order because negative SSI values indicate unstable condition. The atmospheric stability indices were unstable on the heavy-rainfall days compared to that on the no-heavy-rainfall days. For the SSI and K-index values, the 25th percentiles on the heavy-rainfall days and the 75th percentiles on the no-heavy-rainfall days were almost equal in value. In contrast, the value of the 25th percentile for CAPE on the heavy-rainfall days was almost equal to that of the median on the no-heavy-rainfall days. The differences in the atmospheric stability indices between the heavy-rainfall days and the no-heavy-rainfall days were large for the SSI and K-index values and small for CAPE. Therefore, the SSI and K-index values, which show a good association with the occurrence of heavy rainfall, were used in this study to evaluate the atmospheric stability on heavy-rainfall days; in addition, the 25th percentiles on the heavy-rainfall days (SSI = 0.98; K-index = 31.8) were determined as the thresholds of heavy-rainfall occurrence.

Figure 2 shows the relationship between SSI and K-index for July to August in 2011–2013. On heavy-rainfall days, SSI and K-index were both distributed on the unstable side at both 0900 JST (Fig. 2a) and 2100 JST (Fig. 2b). Values of SSI < 0.98 and K-index ≥ 31.8 were generally observed on heavy-rainfall days; however, 13 and 12 of the heavy-rainfall days were outside of these thresholds at 0900 JST and 2100 JST, respectively. It was thought that there are many cases where the time difference between the occurrence of heavy rainfall and the upper-air observation is large (Table 1). In addition, the upper-air data after heavy rainfall were not available when we actually
performed the prediction. Therefore, to predict the occurrence of heavy rainfall, it is necessary to use atmospheric stability at a time close to that of the rainfall event (within a few hours) obtained from upper-air data with high temporal resolution (e.g., regional objective analysis data). However, to evaluate the predictability of heavy rainfall occurrence with these atmospheric stability indices, the results obtained using the daily minimum SSI and the daily maximum K-index are illustrated in Fig. 2c. If the thresholds (SSI < 0.98 and K-index ≥ 31.8) were considered to be criteria of heavy-rainfall occurrence, a total of 94 days satisfied these criteria during the period. 30 days out of 34 heavy-rainfall days satisfied these criteria (probability of detection: 88%). This result implies that atmospheric stability can be evaluated using the upper-air observation data at Tateno, which is located approximately 50 km from the Tokyo Metropolitan area (Fig. 1). However, 64 days out of 152 no-heavy-rainfall days satisfied these criteria (probability of false detection: 42%). Therefore, for the prediction of heavy-rainfall events, it is necessary to consider the convergence of surface winds and the concentration of water vapor in the lower atmosphere as well as atmospheric stability.

In this study, we focused on the heavy-rainfall case that occurred in the Tokyo Metropolitan area on 12 August 2013, and conducted analysis of the distribution and temporal variation in the convergence of surface winds and water vapor. In addition, we compared the temporal variation with no-heavy-rainfall case on 10 August 2013. This day was selected because the pressure pattern was similar to that of 12 August 2013 and the atmosphere was unstable, with the smallest SSI value in no-heavy-rainfall days that satisfied the criteria.
3.2 Relationships between heavy rainfall and distributions of wind convergence and water vapor

Heavy rainfall, which caused flood damage and power outages, occurred in the western part of the Tokyo Metropolitan area on 12 August 2013. According to the weather chart on this day (Fig. 3a), a summer-type pressure pattern was present and disturbances such as typhoons and fronts did not occur in the central part of Japan. The wind system over the Kanto district showed the “E-S-type” wind pattern, in which easterly and southerly winds converged in the vicinity of Tokyo (Fig. 3b). At 0900 JST, the SSI and K-index were $-2.4$ and $35.3$, respectively, indicating that the atmosphere was unstable. At 1710 JST, more than 5 mm of 10-min rainfall was observed for the first time in Itabashi Ward in the Tokyo Metropolitan area. After that, the heavy-rainfall area rapidly increased and a maximum hourly rainfall of 92 mm was observed at Nerima (Shakujii) at 1830 JST.

Figure 4 shows the distributions of 10-min rainfall, wind, and divergence at 20-min intervals from 1720 JST to 1900 JST on 12 August 2013. The solid contour lines represent 10-min rainfall at 5-mm intervals; the dashed contour lines represent 2.5 mm of 10-min rainfall. The distributions of temperature at 1700 JST and 1740 JST are shown in Fig. 5. At 1720 JST (Fig. 4a), a heavy-rainfall area appeared in the northern part of the Tokyo Metropolitan area and moved slowly southward. In contrast, at 1740 JST (Fig. 4b), another heavy-rainfall area appeared in the southwestern part of the Tokyo Metropolitan area and moved northward. At this time, the northeasterly wind from the northern heavy-rainfall area and the southeasterly wind from the southern heavy-rainfall area were converging in the western part of the Tokyo Metropolitan area and Koganei City. Around each
heavy-rainfall area, a marked fall in temperature of approximately 6°C at the maximum was observed from 1700 JST (Fig. 5a) to 1740 JST (Fig. 5b). This fall in temperature and changes in the wind patterns indicated the occurrence of cold outflow from the heavy rainfall areas. Subsequently, at 1800 JST (Fig. 4c), the two heavy-rainfall areas merged and rapidly intensified near Suginami. At 1820 JST (Fig. 4d), 43 mm of 10-min rainfall was observed at Nerima (Shakujii). Although the center of the heavy-rainfall area was located slightly to the north, the heavy-rainfall area corresponded to the large convergence area 40 min previously (Fig. 4b). At this time, the easterly wind from the heavy-rainfall area and the southerly wind converged on the western and southwestern sides of the heavy-rainfall area. Afterwards, at 1840 JST (Fig. 4e) and 1900 JST (Fig. 4f), heavy rainfall was observed in these areas. Thus, the heavy-rainfall areas corresponded to the large convergence area that existed approximately 40 min prior to the heavy rainfall.

Next, we focused on the variation in water vapor associated with the convergence of surface winds and examined the distributions and temporal variations in the PWV and WVC index obtained by the GPS analysis. Figure 6 illustrates the distributions of PWV, the deviation of PWV relative to 40 min previously, and surface winds at 20-min intervals from 1640 JST to 1820 JST on 12 August 2013. At 1640 JST (Fig. 6a), i.e., 30 min before the heavy rainfall was observed for the first time at Itabashi Ward in the Tokyo Metropolitan area, more than 55 mm of PWV was observed in the central part of the Tokyo Metropolitan area. Shoji (2013) demonstrated that the frequency of more than 10 mm of hourly rainfall increases rapidly as PWV exceeds 60 mm. Therefore, it was thought...
that the amount of water vapor in the atmosphere was comparatively large. However, there was no
area in which PWV was remarkably increased relative to 40 min previously, and the same tendency
could also be observed at 1700 JST (Fig. 6b). At 1720 JST (Fig. 6c), PWV was decreased in the
northern part of the Tokyo Metropolitan area, where heavy rainfall was observed, whereas PWV
was raised in the coast of Tokyo Bay and around Koganei City. This decrease in PWV could
correspond to the decrease in water vapor caused by the fall in the atmospheric column temperature
due to the cold outflow near the heavy-rainfall area. At 1740 JST (Fig. 6d), the area of large PWV
was observed in the western side of the heavy-rainfall area. Afterwards, at 1800 JST (Fig. 6e) and
1820 JST (Fig. 6f), this area moved westward and PWV were remarkably increased in the western
side of the heavy-rainfall area. In this way, PWV tended to be large before the occurrence of heavy
rainfall. However, since PWV decreases with decreasing temperature, the remarkable increase in
PWV near the heavy-rainfall area was not distinct at this spatial scale.

Figure 7 illustrates the distributions of the WVC index, its deviation relative to 40 min previously,
and the surface winds at 20-min intervals from 1640 JST to 1820 JST on 12 August 2013. To
develop this distribution map, following Shoji (2013), we first interpolated the atmospheric delay
gradient parameter $G$ into grid points with intervals of approximately 10 km using the objective
analysis of Cressman (1959), and then calculated $\nabla PWV_G$. A positive (negative) value of the WVC
index denotes convergence (divergence) of $\nabla PWV_G$ and the blue (red) color shows an increase
(decrease) in the WVC index relative to 40 min previously. At 1640 JST (Fig. 7a), a positive
deviation of the WVC index was observed in the northern part of the Tokyo Metropolitan area and the WVC index was already large. At that time, the easterly and southerly winds seem to have been converging in this area, but the wind convergence was unclear because there were few observation points in this area. At 1700 JST (Fig. 7b) and 1720 JST (Fig. 7c), the area with a large WVC index was continuously located in the northern part of the Tokyo Metropolitan area. Afterwards, at 1740 JST (Fig. 7d), the area of positive deviation of the WVC index moved to a region in the western part of the Tokyo Metropolitan area and Koganei City. This region corresponded to the area of large wind convergence that occurred at about the same time (Fig. 4b). Thus, this increase in the WVC index is considered to indicate water vapor concentration in the lower atmosphere caused by upward flow from the convergence of surface winds; however, the area of positive deviation of the WVC index was wider than that in wind convergence. It is suggested that the spatial scale of the WVC index is larger than that of wind convergence. Subsequently, the areas of large WVC index and positive deviation of the index moved slowly southward at 1800 JST (Fig. 7e) and 1820 JST (Fig. 7f). Similarly to the surface wind convergence, the increase in the WVC index was observed approximately 40 min prior to the occurrence of heavy rainfall.

3.3 Temporal variation in wind convergence and water vapor

Figure 8 shows the time series of 10-min rainfall, divergence, PWV, WVC index, and 20-min divergence change rate from 1540 JST to 1940 JST on 12 August 2013. Time series are illustrated for the six principal stations where more than 10 mm of 10-min rainfall was observed (Fig. 1).
Divergence is the average value of the four grid points around each observation point, and PWV
and WVC index are the values interpolated by IDW with a 15-km search radius from each
observation point. Increasing convergence (i.e., decreasing divergence) with a rate of divergence
change of less than $-1 \times 10^{-5}$ s$^{-1}$ min$^{-1}$ was observed several tens of minutes before the occurrence
of heavy rainfall at all observation points except for Itabashi. At most of the observation points, the
peak time for convergence was 10–30 min prior to the heavy rainfall, and the increase in
convergence continued for approximately 30 min until the convergence peak time. In contrast,
increasing convergence preceding the heavy rainfall was not clear at Itabashi (Fig. 8a), where the
occurrence of heavy rainfall was earliest, because there was a weak rainfall of less than 5 mm per
10 min prior to the heavy rainfall. Focusing on the temporal variation in water vapor, PWV of more
than 50 mm was observed at all observation points before the heavy rainfall. At Koganei (Fig. 8f),
the increase in PWV was observed prior to the heavy rainfall; however, the temporal variations in
PWV were not clear at the other points. In contrast, the WVC index was already large
approximately two hours prior to the heavy rainfall at all observation points; WVC index values of
approximately $20 \times 10^{-3}$ mm km$^{-2}$ occurred at 1600 JST. The increase in the WVC index was
observed for several tens of minutes prior to the heavy rainfall at all observation points except for
Itabashi. This increase occurred at almost the same time as the increasing convergence, and the peak
of the WVC index occurred approximately 15–40 min after the convergence peak time. However,
the differences in the WVC index between the observation points were small compared to those in
wind convergence. Taking this finding into account, the WVC index might correspond to an increase in water vapor resulting from wind convergence at a larger spatial scale, as illustrated in Fig. 3b.

For comparison with the no-heavy-rainfall case, the temporal variations from 1140 JST to 1940 JST on 10 August 2013 are illustrated in Fig. 9, in the same manner as in Fig. 8. A summer-type pressure pattern was observed on this day, as on 12 August 2013. However, more than 1 mm of 10-min rainfall was not observed in the Tokyo Metropolitan area on 10 August. Though the atmospheric stability indices at 0900 JST (SSI = 0.7; K-index = 24.3) did not satisfy the thresholds, the SSI and K-index at 2100 JST were −3.5 and 36.7, respectively; the atmospheric conditions became unstable to the same degree as on 12 August. PWV also showed a large value of more than 50 mm. The surface wind was generally weak, but penetration of a southerly sea breeze was observed over the western part of the Tokyo Metropolitan area from 1300 JST to 1500 JST (not illustrated in the figure). In response to this sea breeze front, convergence of the surface winds was observed and the minimum values of divergence were almost the same as on 12 August at some observation points. However, the maximum values of the WVC index were approximately $10 \times 10^{-3}$ mm km$^{-2}$ at all observation points, and in contrast to 12 August, a remarkable increase in the WVC index was not apparent. In addition, the absolute values of the divergence change rate were small and increasing convergence that continued for several tens of minutes was not observed.

As mentioned above, the increase in surface wind convergence and WVC index preceding a
heavy rainfall was observed only on a heavy-rainfall day. For evaluating the frequency of occurrence of these features, the temporal variations in wind convergence and WVC index on heavy-rainfall days were examined. Figure 10 shows the percentile values from 60 min before to 30 min after the occurrence of rainfall on the heavy-rainfall days and the no-heavy-rainfall days. The percentile values were indicated for divergence, 20-min divergence change rate, WVC index, and deviation of the WVC index relative to 40 min previously. For calculating the percentile values, we selected observation points from the Tokyo Metropolitan area wherein a maximum of 10-min rainfall was observed when more than 5 mm of 10-min rainfall was observed at 1010–2200 JST. The occurrence of rainfall was defined as the time when more than 1 mm of 10-min rainfall was observed for the first time, and the points wherein the maximum rainfall was observed after 60 min from the occurrence or wherein there was an interruption of rainfall (less than 1 mm of 10-min rainfall) from the occurrence to the maximum time were excluded. From these selected points, we used a cumulative total of 137 points wherein the average divergence value of the four grid points around each point was obtained for divergence and 33 points wherein a daily maximum 10-min rainfall was observed on the heavy-rainfall days for WVC index. The percentile values of all grid points in the Tokyo metropolitan area at 1010–2200 JST on 152 no-heavy-rainfall days are also shown in Fig. 10.

For divergence (Fig. 10a), convergence was observed in approximately three quarters of cases before the occurrence of rainfall, and the decrease in the 25th and the 10th percentiles was observed
10–40 min prior to the occurrence on the heavy-rainfall days. Divergence values of less than $-2.9 \times 10^{-4}$ s$^{-1}$, which corresponds to the 10th percentiles on the no-heavy-rainfall days, were observed in a quarter of cases at 10–30 min prior to the occurrence of rainfall. The divergence change rate (20-min; Fig. 10b) was negative in approximately half of cases before the occurrence of rainfall, and a rate of divergence change of less than $-0.67 \times 10^{-5}$ s$^{-1}$ min$^{-1}$, which corresponds to the 10th percentiles on the no-heavy-rainfall days, was observed in more than a quarter of cases at 10–30 min prior to the occurrence. In contrast, the median for the WVC index (Fig. 10c) on the heavy-rainfall days already exceeds the 75th percentiles on the no-heavy-rainfall days ($3.6 \times 10^{-3}$ mm km$^{-2}$) at 60 min before the occurrence, and it was almost equal to the 90th percentiles on the no-heavy-rainfall days ($7.6 \times 10^{-3}$ mm km$^{-2}$) at 10 min before the occurrence of rainfall. WVC index showed a gradual increase before the occurrence of rainfall, and in many cases, the difference in the WVC index between the heavy-rainfall days and the no-heavy-rainfall days was already large from 60 min before the occurrence. Deviation of the WVC index relative to 40 min previously (Fig. 10d) on the heavy-rainfall days was positive values in more than half of cases before the occurrence of rainfall. The deviation of WVC index of more than $3.5 \times 10^{-3}$ mm km$^{-2}$, which corresponds to the 90th percentiles on the no-heavy-rainfall days, was observed in more than a quarter of cases at 5–40 min prior to the occurrence. Thus, the increase in surface wind convergence and WVC index preceding the heavy rainfall that was rarely observed on the no-heavy-rainfall days was observed in more than a quarter of cases on the heavy-rainfall days. This result indicates that it is possible to
predict occurrences of heavy rainfall several tens of minutes prior by monitoring these features obtained from high-density observation of surface wind and water vapor.

4. Conclusion

To evaluate the atmospheric features on heavy-rainfall days, atmospheric stability indices that show good association with the occurrence of thunderstorms were examined. Most heavy-rainfall days could be detected using threshold values of SSI and K-index (SSI < 0.98 and K-index ≥ 31.8). However, because several no-heavy-rainfall days also satisfied these criteria, it was thought that, in addition to atmospheric stability, the convergence of surface winds and the concentration of water vapor in the lower atmosphere must be considered to predict occurrences of heavy rainfall.

The relationships between rainfall distribution on 12 August 2013, and the convergence of surface winds and water vapor were examined using high-density data obtained from meteorological observations in central Tokyo. The area of heavy rainfall showed good agreement with the wind system and the convergence of surface winds tended to increase several tens of minutes prior to the heavy rainfall. The peak time of wind convergence was 10–30 min before the heavy-rainfall occurrence, and the increasing convergence continued for approximately 30 min until the convergence peak time. Around the heavy-rainfall area, the increase in the WVC index coincided with the increase in convergence. In contrast, the WVC index was already large approximately two hours prior to the heavy rainfall and the peak time of the WVC index was later.
than that of wind convergence. This result suggests that the temporal and spatial scales of the WVC index are larger than that of the surface wind convergence obtained from the high-density data in this study. However, it is thought that the WVC index and convergence of surface winds represent the concentration of water vapor at each spatial scale.

In addition, the increase in surface wind convergence and WVC index preceding the heavy rainfall that was rarely observed on the no-heavy-rainfall days was observed in more than a quarter of cases on the heavy-rainfall days. Although it is necessary to examine the appropriate combination of thresholds to predict occurrences of heavy rainfall, the increase in the WVC index and wind convergence as well as atmospheric stability can be used for prediction of heavy-rainfall occurrence. Therefore, by monitoring the temporal variations and distributions of these parameters using a high-density observation network, we consider that it is possible to predict occurrences of heavy rainfall rapidly and accurately.

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| Year | Date   | Occurrence time (1010-1400) (JST) | 10-min rainfall (mm) | Date   | Occurrence time (1410-1800) (JST) | 10-min rainfall (mm) | Date   | Occurrence time (1810-2200) (JST) | 10-min rainfall (mm) |
|------|--------|----------------------------------|----------------------|--------|----------------------------------|----------------------|--------|----------------------------------|----------------------|
| 2011 | 3 Aug  | 1250                             | 15.0                 | 1 Jul  | 1450                             | 11.0                 | 5 Jul  | 1830                             | 14.5                 |
|      | 4 Aug  | 1400                             | 16.0                 | 20 Jul | 1600                             | 9.0                  | 30 Jul | 2030                             | 11.0                 |
|      | 5 Aug  | 1400                             | 8.0                  | 7 Aug  | 1600                             | 15.9                 |        |                                  |                      |
|      | 19 Aug | 1050                             | 15.0                 | 11 Aug | 1510                             | 10.2                 |        |                                  |                      |
|      |        |                                  |                      | 12 Aug | 1800                             | 6.0                  |        |                                  |                      |
|      |        |                                  |                      | 26 Aug | 1530                             | 33.8                 |        |                                  |                      |
|      | 4 Aug  | 1450                             | 5.8                  | 7 Jul  | 1930                             | 8.0                  | 18 Jul | 2110                             | 5.0                  |
|      | 11 Aug | 1220                             | 12.0                 | 15 Aug | 1220                             | 6.2                  |        |                                  |                      |
|      | 18 Aug | 1100                             | 15.5                 | 23 Aug | 1650                             | 22.6                 |        |                                  |                      |
| 2012 | 20 Jul | 1350                             | 5.2                  | 26 Jul | 1600                             | 7.2                  | 3 Jul  | 1830                             | 5.0                  |
|      | 6 Aug  | 1140                             | 17.0                 | 4 Aug  | 1450                             | 5.8                  | 7 Jul  | 1930                             | 8.0                  |
|      | 11 Aug | 1220                             | 12.0                 |        |                                  |                      | 18 Jul | 2110                             | 5.0                  |
|      | 15 Aug | 1040                             | 6.2                  |        |                                  |                      |        |                                  |                      |
|      | 18 Aug | 1100                             | 15.5                 |        |                                  |                      |        |                                  |                      |
| 2013 | 8 Jul  | 1620                             | 20.0                 | 7 Jul  | 1740                             | 18.0                 | 18 Jul | 2110                             | 14.0                 |
|      | 14 Jul | 1650                             | 18.0                 | 8 Jul  | 1620                             | 20.0                 | 27 Jul | 1930                             | 15.0                 |
|      | 23 Jul | 1610                             | 29.0                 | 14 Jul | 1650                             | 18.0                 | 12 Aug | 1820                             | 43.0                 |
|      | 6 Aug  | 1520                             | 21.0                 | 23 Jul | 1610                             | 29.0                 | 22 Aug | 2020                             | 11.0                 |
|      | 11 Aug | 1530                             | 10.0                 |        |                                  |                      |        |                                  |                      |
|      | 21 Aug | 1620                             | 22.6                 |        |                                  |                      |        |                                  |                      |
|      | 23 Aug | 1450                             | 10.0                 |        |                                  |                      |        |                                  |                      |
Table 2. The percentile values of SSI, K-index, and CAPE at 0900 JST on the heavy-rainfall days and the no-heavy-rainfall days. The SSI values are arranged in descending order.

|                   | SSI       | K-index   | CAPE      |
|-------------------|-----------|-----------|-----------|
|                   | Heavy-rainfall days | No-heavy-rainfall days | Heavy-rainfall days | No-heavy-rainfall days | Heavy-rainfall days | No-heavy-rainfall days |
| maximum           | -3.11     | -2.58     | 41.2      | 40.3      | 3136      | 2486      |
| 75th percentile   | -1.50     | 1.00      | 37.4      | 32.7      | 937       | 565       |
| median            | 0.03      | 2.68      | 34.5      | 29.2      | 610       | 155       |
| 25th percentile   | 0.98      | 4.69      | 31.8      | 21.9      | 112       | 0         |
| 10th percentile   | 2.12      | 6.48      | 21.6      | 13.3      | 1         | 0         |
| minimum           | 4.87      | 17.12     | -0.7      | -32.5     | 0         | 0         |