CHARACTERISTICS OF PRECIPITATION SYSTEM IN HIROSHIMA PREFECTURE DURING THE HEAVY RAINFALL EVENT OF JULY 2018 OBSERVED USING XRAIN DATA

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Heavy rainfalls with band-shaped precipitation systems poured on the western part of Japan from June 28 to July 8, 2018, causing flooding and sediment disasters over Hiroshima Prefecture. At the same time, the Ministry of Land, Infrastructure and Transport (MLIT) had operated the eXtended RAdar Information Network (XRAIN) consisting of X-band Multi-Parameter (MP) radars and C-band MP radars. This study clarifies the process and mechanism of the heavy rainfalls based on the meteorological conditions calculated using the MesoScale Model (MSM) of the Japan Meteorological Agency (JMA) and the XRAIN data over Hiroshima Prefecture.

We obtained the following findings. First, compared to rain gauges, XRAIN captured the spatio-temporal distribution of rainfall intensity with high accuracy. Second, three-dimensional rainfall intensity, generated by the Cressman interpolation of two X-band MP radars, allowed us to visualize the evolution of the band-shaped precipitation systems. Third, the cloud top of the band-shaped precipitation system reached an altitude of less than 8,000 m, which was low compared to the convective heavy rain on August 20, 2014. Finally, the high rainfall intensity recorded near Hiroshima Station at 1805 local standard time (LST) July 6, 2018, was due to the band-shaped precipitation system with sufficient water vapor supply from the south and atmospheric instability.

Key Words : XRAIN, band-shaped precipitation system, water vapor flux, atmospheric instability

1. INTRODUCTION

From June 28 to July 8, 2018, Typhoon Prapiroon and the Baiu front caused record-breaking heavy rains across Japan, leading to flooding of rivers, sediment disasters, and traffic interruptions simultaneously. In Hiroshima Prefecture, many areas recorded maximum rainfall for 24 hours, 48 hours, and 72 hours in observation history. In Hiroshima Prefecture, a rainfall warning was issued for Hatsukaichi City at 0808 LST July 5, and a special heavy rain warning was issued for more expansive areas including Hiroshima City and Kure City at 1940 LST July 6. In the early evening of July 6 and early morning of July 7, localized heavy rainfalls with band-shaped precipitation systems overlapped with the prolonged rain in Hiroshima Prefecture. As a result, 12 rivers and 82 rivers under the management of Hiroshima Prefecture experienced levee breach and overflow, respectively. At the same time, sediment disasters took place in many areas, including Kure City (172 cases), Takehara City (70 cases), and Hiroshima City (62 cases), totaling 624 cases, which took many lives. The damage exceeded those in recent major sediment disasters on June 29, 1999 and August 20, 2014 in Hiroshima Prefecture. The Japan Meteorological Agency (JMA) named this calamity “the Heavy Rain Event of July 2018,” and the Cabinet Office designated it as a major disaster.
Recently, band-shaped precipitation systems have attracted much attention from researchers because of their contribution to localized heavy rain. Combing the observation and the numerical analysis of downpours, the Meteorological Research Institute discussed the cause of heavy rain in Hiroshima City on August 20, 2014. It explained that the back-building mechanism generated band-shaped precipitation systems and that a large amount of water vapor supply in the atmospheric boundary layer promoted the development of cumulonimbus clouds.

A similar formation of band-shaped precipitation systems was observed during a heavy rain event in northern Kyushu in July 2017. The Meteorological Research Institute indicated that a large volume of water vapor invaded the lower layer at the presence of cold air in the upper layer, which helped clusters of cumulonimbus to develop. However, it did not discuss the development and attenuation of band-shaped precipitation systems with individual cumulonimbus and atmospheric instability.

In a study of the Heavy Rain Event of July 2018, Tanaka showed the self-replacement process of precipitation cells using a planar distribution of rainfall intensity obtained from XRAIN. Nakakita et al. created three-dimensional maps of radar reflection intensity from X-band MP radars in the Kinki Region. Their study demonstrated the possibility and need for a more detailed analysis of precipitation systems.

The present study aims to clarify the three-dimensional structure of the precipitation system that led to the heavy rain in Hiroshima Prefecture in July 2018. To this end, it combines the numerical products of MSM and the observed data by XRAIN and by ground rain gauges.

2. METEOROLOGICAL CONDITIONS

We employed the products of MSM of JMA to understand the meteorological conditions of the Heavy Rain Event of July 2018, with emphasis on the Baiu front. In MSM, ground physical values are calculated at 5-km grid intervals, while the barometric surface physical properties are given at 10-km grid intervals. The MSM products are updated at three-hour breaks. The MSM products provide altitude of barometric surfaces, as well as wind, temperature, vertical wind, and relative humidity on each barometric surface. We used these values to obtain potential temperature, relative potential temperature, water vapor mixing ratio, water vapor flux, and Showalter stability index.

Fig. 1 shows the surface weather maps for 0900 LST July 6 and 0900 LST July 7, 2018. At 0900 LST July 6, the Baiu front stayed in the east-west direction over Hiroshima Prefecture. At 0900 LST July 7, the Baiu front moved in the SW–NE direction. Fig. 2 shows the fields of potential temperature and water vapor mixing ratio at the 925 hPa altitude, which are averaged over two days from 0000 LST July 6 to 2400 LST July 7. The potential temperature in the lower layer in Fig. 2(a) shows that the air mass over the East China Sea and the Pacific Ocean carried a potential temperature of 300 K or more and blew over the Japanese archipelago from south and southwest.

Meanwhile, there was cold air mass over the Sea of Japan and the Sea of Okhotsk. The two air masses created a large temperature gradient. On the other hand, Fig. 2(b) shows the water vapor mixing ratio in the lower layer around Japan and that an extremely humid air with 16 g/kg above the East China Sea and the Pacific Ocean flowed into Japanese islands. The Baiu front stayed near 130° E and 33° N with a steep gradient of water vapor mixing ratio. This is consistent with the characteristics of the Baiu front in a previous study.

Fig. 3 illustrates the total water vapor flux in the lower layer (700 hPa to 1,000 hPa) from 1800 LST July 6 to 0300 LST July 7. The total water vapor flux was calculated as follows:

\[
\tilde{q}_{\text{flux}} = \frac{1}{g} \int_{700}^{1000} \tilde{w} \tilde{d}p \tag{1}
\]

where \(\tilde{q}_{\text{flux}}\) = water vapor flux, \(g\) = gravitational
acceleration, \( \vec{v} \) = wind speed vector, and \( w \) = water vapor mixing ratio. Fig. 3 clearly shows the inflow of a high water vapor flux into western Japan from near the Nansei Islands at 1800 LST July 6 and 0300 LST July 7. Combining Fig. 2 showing strong wind of 10 m/s or more in the lower layer in the southwest of Japan and the high sea surface temperature, we can infer that a continuous supply of vast amounts of water vapor over the Japan Islands contributed to the heavy rainfalls. Kato further indicated that the water vapor supply in the lower layer was one of the most influential meteorological factors to generate band-shaped precipitation systems.

Fig. 4 shows the Showalter stability index (SSI). It is defined by the difference between the temperature at 500 hPa of an air parcel that is lifted from 850 hPa to 500 hPa, first dry-adiabatically to saturation, then moist-adiabatically and the surrounding temperature at 500 hPa. SSI is a severe weather index, and more negative SSI values indicate greater atmospheric instability. SSI value between +1 °C and -2 °C implies thundershowers while its value of -3 °C or lower suggests severe thunderstorms. Fig. 4 demonstrates that at 1800 LST July 6, large areas of western Japan showed SSI values of +1 °C or lower, as well as lower values across Hiroshima Prefecture. Hence, it can be said that the invasion of a large amount of warm and humid air towards the Baiu front made the atmosphere highly unstable and triggered precipitation. On the other hand, at 0300 LST July 7, SSI values across Hiroshima Prefecture increased. Cold, dry air from the north pushed the front southward over Hiroshima Prefecture, relaxing the atmospheric instability.

Fig. 5 shows the distributions of relative humidity and wind velocity at 700 hPa altitude averaged from 0000 LST July 6 to 2400 LST July 7. Humid air with a relative humidity of 90% or higher, or the moist tongue, extended from the East China Sea to the Kanto Region.
in Japan, which testified to the active evolution of rain clouds. The warm and humid air supply in the lower atmospheric layer met the conditions of band-shaped precipitation systems described by Kato.

Fig.6 gives the vertical distribution of relative potential temperature averaged over two days from 0000 LST July 6 to 2400 LST July 7 along 132.5° E, where Hiroshima City is located. It shows that relative potential temperature is vertically constant at around 34.4° N. Formation of the Baiu front over Hiroshima Prefecture led to neutral stratification through vertical mixing due to convection. The atmosphere became unstable and stable in the south and north of the Baiu front, respectively.

3. WEATHER RADAR OBSERVATIONS

(1) Weather radars
Fig.7 shows the location of weather radars and ground rain gauges in Hiroshima. The red circles show the quantitative observation range for the X-band MP radar (60 km), while the black circles show the qualitative observation range of 80 km. MLIT installed a pair of X-band MP radars on Mount Ushio in the east and Mount Nogaibara in the west of Hiroshima City. Similarly, X-band MP radars were installed on Mount Tsune and Mount Kuma in Okayama Prefecture, which partly covers the eastern part of Hiroshima Prefecture. MLIT also has operated C-band MP radars on Mount Rakan in Yamaguchi Prefecture and Mount Owa in Okayama Prefecture, which can capture the rains in Hiroshima Prefecture. In this study, we used the observed data at 302 ground rain gauges together with XRAIN data. Fig.8 shows the distribution of 72-hour precipitation from 0000 LST July 5 to 2400 LST July 7, which was observed by XRAIN. The area with the rainfall amount of 250 mm or more extended over Hiroshima Prefecture and the heavy rainfall of 400 mm or higher occurred in the south of Hiroshima Prefecture.

(2) Characteristics of heavy rains by weather radar
a) Accuracy of the weather radar
We checked the accuracy of XRAIN through a
comparison against the observed data by ground rain gauges from 0000 LST July 5 to 1200 LST July 7, 2018. The result is shown in Fig. 9, where 10-minute rainfall intensity by the ground rain gauge is plotted against the XRAIN data immediately above the relevant ground rain gauge. The regression analysis reports that the total precipitation captured by XRAIN recorded 0.885 of the total rainfall measured by ground rain gauges over the test period. The result indicates that XRAIN tended to underestimate the rainfall amount. As seen in Fig. 9, XRAIN tends to underestimate the precipitation by rain gauges, especially for heavy rain exceeding 80 mm/h.

Fig. 10 compares hyetographs of ground rain gauges and XRAIN at two stations, where severe flood damage took place, i.e., Hiroshima Station in the Ota River basin and Hongo Station in the Nuta River basin (Fig. 8). The error bar in the figure shows the maximum and minimum of XRAIN data within a radius of 1,500 m from the stations. The error bar is introduced because the rainfall intensity observed by XRAIN may not agree with the data measured by the ground rain gauge immediately below due to the wind effects. At Hiroshima Station, the ground rain gauges recorded the value of 108 mm/h at 1810 LST July 6, and rainfall events whose intensity exceeded 20 mm/h occurred several times early in the morning of July 7. XRAIN successfully captured their occurrence with reasonable magnitude and accurate timing. At Hongo Station, two heavy rain events occurred: one with rainfall intensity of 72 mm/h at 2110 LST July 6 and the other in the early morning of July 7. XRAIN tended to underestimate the heavy rain somewhat, but otherwise well-produced the hyetograph observed by the ground rain gauge.

b) Three-dimensional characteristics of the precipitation system

Using the two X-band MP radar rain gauges installed in Hiroshima Prefecture, we visualized the three-dimensional structure of the cloud clusters that brought about heavy rains. X-band MP radars have operated Constant Altitude Plan Position Indicator (CAPPI) observation for early detection of heavy rains and analysis of rain cloud structure. CAPPI observation uses 12 angles of altitudes from 0.2 to 20 degrees for 5 minutes. The observed values were transformed onto arbitrary
three-dimensional grids at 5-minute intervals with the interpolating formula by Cressman:

\[ R_s = ar + b \quad (2) \]
\[ W_i = w_{h,i}w_{v,i} \quad (3) \]
\[ w_{h,i} = \frac{1}{1 + C_h \left( \frac{d_i}{R_s} \right)^2} \quad (4) \]
\[ w_{v,i} = \frac{1}{1 + C_v \left( \frac{h_i}{H} \right)^2} \quad (5) \]
\[ V_g = \frac{\sum W_iV_i}{\sum W_i} \quad (6) \]

where \( R_s \) = radius of the circle of influence (km), \( r \) = distance from the radar site, \( a = 0.013, b = 0.15 \) (km), \( W_i \) = weight function, \( w_{h,i} \) = horizontal weight function, \( w_{v,i} \) = vertical weight function, \( C_h = 0.5, C_v = 20, d_i \) = horizontal distance between a grid point and an observation point (km), \( h_i \) = vertical distance between a grid point and an observation point (m), \( H = 5000 \) (m), \( V_i \) = observed value at an observation point, and \( V_g \) = interpolated value at a grid point. Horizontal resolution was 1 km while vertical resolution was from 500 m and up to 10 km but 1 km above that height. This was because there were less data in the higher altitude.

Fig. 11 shows the horizontal distribution of rainfall intensity at 2000 LST July 6, when a downpour rain was going to fall on Hongo Station. Fig. 12 gives a three-dimensional view of a train of cumulonimbus clouds from the direction indicated by the arrow in Fig. 11. In the figure, the vertical scale is expanded by 2 to enhance visibility. Compared to Fig. 11, it is clear that band-shaped precipitation systems extends from the eastern part of Hiroshima Bay to Hongo Station from 1945 LST to 2020 LST. A closer look inside the band-shaped precipitation systems indicates that a row of cumulonimbus clouds develops and dissipates downwind. It also demonstrates that the new development of cumulonimbus takes place on the upwind side. This production of a training set of precipitation cells dropped a large amount
of rain over the same area. The analysis of XRSlN data evaluated that the altitude of cumulonimbus with rainfall intensity of 1 mm/h or more was less than 8 km. The cloud height was lower, and the rainfall area was broader than that in the thunderstorm on August 20, 2014, in Hiroshima\textsuperscript{15).

c) Structure of the band-shaped precipitation systems that caused peak rainfall
For the band-shaped precipitation systems that dropped peak rainfall intensity at Hiroshima and Hongo Stations, we compared rainfall intensity by X-band MP radars and water vapor flux and vertical wind shear by MSM.

Fig.13 shows the horizontal distribution of rainfall intensity and vertical cross-section of the band-shaped precipitation systems at three different times. The upper figures correspond to the rain at 1805 LST July 6, when Hiroshima Station recorded the peak rainfall intensity. The middle and the lower figures show the rainfalls at 2105 LST July 6 with the first peak precipitation at Hongo Station and 0405 LST July 7 with the second peak rain at Hongo station, respectively. At 1805 LST July 6, the rainfall area had spread horizontally with band-shaped precipitation systems in SW–NE directions. The center of the cumulonimbus cloud was passing over Hiroshima Station. The rainfall intensity at 4 km altitude shows a high value, indicating the existence of very active convection.

Fig.13 Map distribution and vertical cross-section of rainfall intensity at 1805 LST and 2105 LST on July 6\textsuperscript{th}, and 0405 LST on July 7\textsuperscript{th}. The unit of the scale bar is 2 km.
MSM produced the distribution of water vapor flux and vertical shear of the horizontal wind speed at 950 hPa and 700 hPa altitudes above Hiroshima Prefecture at 1800 LST and 2100 LST July 6 and 0300 LST July 7 as shown in Fig.14. Water vapor flux exceeding 800 kg/m/s flew into Hiroshima Bay at 1800 LST July 6. The wind speed distribution that rotated clockwise in the higher altitude generated strong vertical shear. Kita et al. showed the existence of strong vertical shear in back-building band-shaped precipitation systems during the Heavy Rain Event of August 2014 in Hiroshima. Seko17) also reported the formation of vertical shear in his numerical experiment in back-building band-shaped precipitation systems. Thus, the generation mechanism of band-shaped precipitation systems on July 6 was assumed to be back-building where cumulonimbus clouds were generated sequentially in the opposite direction to their movement.

At 2105 LST July 6, although Hongo Station was at the center of the band-shaped precipitation systems, rainfall intensity was not as strong as in Hiroshima at 1805 LST. The water vapor flux over Hiroshima Bay at 2100 LST July 6 was not high, as shown in Fig.14. Hence it was assumed that the less supply of water vapor reduced the rainfall intensity. At 0405 LST July 7, Fig.13 shows that Hongo Station is located at the front tip of the band-shaped precipitation system, and rainfall intensity is not as strong as in Hiroshima at 1805 LST. On the other hand, the area in the southwest direction shows heavy rainfall, and the rain area takes a tapering shape. The water vapor flux in Fig.14(c) becomes similar to that at 1800 LST July 6 in Fig.14(a). However, in terms of vertical shear in the upper atmosphere, wind speed distribution at 950 hPa and 700 hPa altitudes are perpendicular to each other. The formation of vertical shear is consistent with the characteristics of back and side building storms described by Seko17).

Meanwhile, Fig.4 shows that SSI does not have a low value over Hiroshima Prefecture at 0300 LST July 7. Hence, the atmosphere is not so unstable for cumulonimbus clouds above Hiroshima Bay to develop. We assumed that the two peaks at Hongo Station were brought by attenuating cumulonimbus clouds and that the rainfall intensity did not show high value.

4. CONCLUSIONS

This study clarifies the process and mechanism for the heavy rainfalls based on the meteorological conditions calculated using the MSM of JMA and the XRAIN data over Hiroshima Prefecture. The following are the findings of this study:

- The Baiu front stayed across the Japanese archipelago. A large amount of warm, humid air flew toward the Baiu front from the south and southwest directions.
- The 72-hour precipitation exceeding 400 mm occurred in the southern part of Hiroshima Prefecture. XRAIN can capture the hyetograph of ground rain gauge with high accuracy except for the rainfall intensity exceeding 80 mm/h.
- Three-dimensional distribution of rainfall intensity showed that a new precipitation cell was generated in the opposite direction to the movement in the band-shaped precipitation system with a series of cumulonimbus clouds. During the heavy rain period, there were multiple band-shaped precipitation systems. The band-shaped precipitation system that caused the peak of rainfall at Hiroshima Station at
1805 LST July 6 belonged to a back-building type. The band-shaped precipitation system at 0405 LST July 7 was a back- and side-building type. As the atmospheric instability decreased with the southern migration of the front, convection ceased to be as active as at 1805 LST July 6.

ACKNOWLEDGMENTS: The XRAIN dataset used in this study was collected and provided by the data integration analysis system (DIAS) commissioned by the Ministry of Education, Culture, Sports, Science and Technology – Japan. MSM data were provided by the Research Institute for Sustainable Humanosphere Data Server, Kyoto University. We would like to extend our utmost appreciation to these groups.

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(Received August 31, 2020)
(Accepted November 16, 2020)