DEVELOPMENT OF EARLY LOCAL HEAVY RAINFALL FORECAST TECHNIQUE AT OSAKA CITY

Toshio NAKANO1, Yasushi SUZUKI2 and Aritoshi MASUDA3

1Member of JSCE, Disaster Prevention Division, Japan Weather Association
(3-1-1, Higashi-Ikebukuro, Toshima-ku, Tokyo 170-6055, Japan)
E-mail: toshio@jwa.or.jp

2Member of JSCE, Japan Weather Association (3-1-1, Higashi-Ikebukuro, Toshima-ku, Tokyo 170-6055, Japan)
E-mail: suzuki@jwa.or.jp

3Member of JSCE, Graduate School of Engineering, University of Kyoto (Gokasho, Uji, Kyoto 611-0011, Japan)
E-mail: masuda@hmd.dpri.kyoto-u.ac.jp

In Japan, flooding damage in urban areas caused by local heavy rainfall has increased in recent years. It is of great importance to improve the precision of forecasting local heavy rainfall. However, the present weather forecasting system cannot forecast the local heavy rainfall well in advance since local heavy rainfall has small scale and builds up suddenly. In this study, therefore, we develop two early local heavy rainfall forecast techniques at Osaka City. One is the weather index technique, and the other is the numerical weather forecasting technique that assimilates the X-band multiparameter radar (X-MP). As a result, we can forecast local heavy rainfall earlier by the weather index technique, and we can express the movement, strength, and detailed structure of local heavy rainfall using the numerical weather forecasting technique by assimilating X-MP.

Key Words : local heavy rainfall, data assimilation, X-band multiparameter radar

1. INTRODUCTION

In Japan, the water-retaining function has declined with urbanization, and the tolerance against heavy rainfall has decreased. In cities, sewage systems are being developed assuming about 50 mm/hour heavy rainfall. However, in recent years, flood damage has increased due to heavier rainfall than expected. It has been pointed out that with global warming, the frequency of heavy rainfall will increase in the future; thus, improvement in anti-inundation measures and rainfall prediction is an urgent issue. In response, the Japan Meteorological Agency (JMA) provides High-resolution Precipitation Nowcast for a few hours ahead. On the other hand, the Ministry of Land, Infrastructure, Transport, and Tourism (MILT) observes rainfall with X-MP, and is developing a method to estimate high-precision and high-resolution rainfall distribution, or a Very-short-range Forecasting of Precipitation (VSRF hereafter) that uses rainfall distribution information (e.g., Kato et al.1). In addition, Nakakita et al.2 focused their study on earlier detection of very localized torrential rainfall using X-MP. With these efforts, in recent years, improvements have been made for fast and high-precision understanding of the current rainfall and VSRF. However, VSRF is a method that forecasts rainfall by estimating movements in the rainy areas, and has issues such as its inability to forecast development of rainfall other than by extrapolation based on topographic effect and precipitation changes. Thus, the position of a newly developed rainy area and the rapid growth of a rainy area in a wind convergence zone cannot be forecasted. As a result, a tendency developed where the longer the prediction time, the less accurate the prediction. Thus, the forecast accuracy of local heavy rainfall rapidly developing in urban areas is not sufficient.

On the other hand, forecast methods using numerical weather prediction models such as MSM (Meso Scale Model) operated by JMA can run longer time-frame forecasts compared to the VSRF. With this method, the development process of rain can be expressed based on the atmospheric dynamics. However, the forecast accuracy of the numerical weather prediction model depends on the reproduction accuracy of three-dimensional distribution of
cloud and wind in the initial time, and there is a problem with the insufficient density of the observation values to prepare this initial distribution (e.g., Kawabata et al. 3)). Therefore, it is important to make effective observations using tools, such as radars, to accurately express the 3D distribution of clouds and wind in the initial stage as much as possible. However, though MSM has assimilated a C band radar developed by JMA, it does not use X-MP developed by MILT. Also, forecast with the numerical prediction model requires a large amount of calculation resources and time; thus, it is not suited for early warning.

Therefore, in this research, we defined “urban heavy rainfall” as local heavy rainfall that can damage cities, and aimed to develop a technique to forecast such rain. Here, we did not target torrential rain due to typhoons and weather front activities; instead, we targeted local heavy rainfall that builds up rapidly in urban areas. Local heavy rainfall like this is called “guerrilla torrential rain,” because it causes damage by building up rapidly. Thus, early forecast is important. Osaka prefecture was chosen as the target area as it received the heaviest rainfall on record at 77.5 mm/hour in the Automated Meteorological Data Acquisition System (AMeDAS) in 2011.

Two forecast methods were developed: (i) a method that forecasts by index and is suitable for early warning for urban heavy rainfall that builds up rapidly, and (ii) a method that uses numerical weather prediction model that can obtain detailed distribution over a long time.

2. RECENT URBAN HEAVY RAINFALL IN OSAKA

Recent urban heavy rainfalls that did significant damage have occurred during the day in summer, bringing heavy rainfall to urban areas. Therefore, the target time was set as day hours in summer time. However, since X-MP used in this research was deployed in 2010, the target period was set from 2010 to 2012. Urban areas in Osaka were chosen as the location, and the definition of urban areas was as follows: points that are 20% or higher in the ratio of high-rise buildings and low-rise buildings in urban land use subdivision mesh data published by the Geospatial Information Authority of Japan at third mesh (spatial resolution of 1km) (Fig.1). The urban rainfall was defined at 25 mm/hour or more. The amount of precipitation was obtained from Radar/Rain gauge-Analyzed Precipitation (referred to here as “R/A”) with a spatial resolution of 1km. R/A shows one-hour cumulative rainfall. When the above information is summarized, selection conditions for urban heavy rainfall in Osaka in this study are as follows:

(a) Time: 13:00 to 17:00 hours,
(b) Period: July to September in 2010 to 2012,
(c) Location: urban areas in Osaka
(d) Determination of urban heavy rainfall: precipitation amount is 25 mm/hour or more in urban areas.

If urban heavy rainfall incidents in Osaka were selected with the above conditions, there were three cases in 2010, two cases in 2011, and eight cases in 2012: total of 13 cases. There was a larger number of urban heavy rainfall present in 2012 because in August and September, Pacific High was strong, and the atmospheric condition was unstable. The case with the worst damage occurred on August 27, 2011. In AMeDAS, Osaka received the heaviest rainfall on record at 77.5 mm/hour. A total of 97 houses had been flooded above floor level, and a total of 1,647 houses below floor level, while roads were flooded at 73 locations.

3. CHARACTERISTICS OF URBAN HEAVY RAINFALL IN OSAKA

Characteristics of urban heavy rainfall in Osaka are summarized with the case of August 27, 2011, when the damage was the worst. On that day, a typhoon formed on the south of Japan, and the warm humid flow came from the south. Looking at the temporal change in R/A (Fig.2), rain that started
around 15:00 rapidly developed until 16:00, leading to extremely heavy rain in Osaka. In addition, rainfall became strong again in Hyogo prefecture, and at 18:00, 53.5 mm/hour heavy rainfall was recorded in Miki.

We will not present a graph here, but if we outline the atmospheric condition in Osaka at this time with the MSM initial value at 9:00 on August 27, the 925 hPa surface in the lower layer had a flow from the south with high equivalent potential temperature (342.7 K at a grid point near Osaka in AMeDAS), while cold inflow was present at the upper layer of 500 hPa and 339.3 K. It was an unstable condition in which the equivalent potential temperature was higher in the lower layer than in the upper layer. The K index that indicates the instability was 35.1, which was extremely high, and it was a condition wherein local heavy rainfall easily occurs. Many instability indices have been proposed, but Nomura and Take-mi\textsuperscript{4)} evaluated the accuracy of MSM, and indicated that the statistical significance of K index calculated from MSM was high for local heavy rainfall. Thus, in this study, we used the K index for instability. K index is:

$$K/I = (T_{s50} - T_{s50}) + T_{d550} - (T_{d500} - T_{d700})$$  \hspace{1cm} (1)

The higher the value, the higher the instability. $T$ is temperature, $T_d$ is dew point temperature, and subscripts are the altitude.

Next, to see the conditions in the Kinki region at the time of urban heavy rainfall, distribution of temperature/atmospheric pressure/wind is shown in Fig.3. Here, for the temperature, 10-minute observation value from AMeDAS was used. Similar to Nakanishi and Hara\textsuperscript{5)}, it was corrected for the mean sea level with the temperature lapse rate of 0.0065 K/m, and sequential correction technique was used to interpolate for grid interval of 1 km. In the same manner as for temperature, atmospheric pressure was horizontally interpolated using mean sea level barometric pressure observation values from meteorological observatories. Wind was presented for each point by correcting for the altitude of 10 m using the 1/7th wind profile power law.

At 14:00, two hours before the urban heavy rainfall started in Osaka, the temperature in Osaka was high at 32.5°C, and heat low formed, with atmospheric pressure being lower than in the surrounding area. Wind from the west came from Osaka Bay and from the east from Ise Bay and converged around the city of Osaka where heat low formed. On that day, the Kinki region was covered in warm and humid air
due to the influence of the edge flow of the typhoon. But the temperature dropped in the Kii Mountain Range, where it was raining, forming a cold area (cold pool). Compared to the city of Osaka, the temperature was 3°C to 4°C lower. At 16:00, when urban heavy rainfall occurred in the city of Osaka, the temperature of the city of Osaka dropped to 23.6°C (a drop of 8.9°C in two hours), and the wind direction changed to southeast wind. On the east side of the cold pool, there was a wind from the east, and on the west side, there was a warm wind from the west (Osaka Bay), creating a strong convergence in addition to a large temperature gradient between the cold pool and high-temperature area. We believe that this convergence promoted a stronger rainfall. Divergent wind was present in the cold pool up to the edge of the pool; thus, the edge of the pool with a cold air outflow was the gust front. Such characteristics of heavy rainfall have been seen in other cases as well. Therefore, urban heavy rainfall in Osaka can be said to occur under (1) unstable field, (2) high temperature in urban areas, and (3) stronger convergence of cold air outflow.

Figure 4 shows the VSRF and MSM forecast values by JMA at this time. However, those of MSM have about 2 hours and 30 minutes delay; thus, at 15:00, it presents the forecast results for 12:00, which became available at 15:00. Both VSRF and MSM at this time forecasted the rain in the Kii Mountain Range. But, heavy rainfall in Osaka at 16:00 and heavy rainfall in Hyogo at 18:00 were not forecasted. This is because VSRF cannot forecast clouds that develop rapidly. MSM did not forecast the heavy rain in Osaka at 16:00, and instead only forecasted the rain of about 30 mm/hour for 18:00. This is likely because (1) initial values of MSM have insufficient accuracy, and (2) grid interval was rough, making it difficult to express such heavy rainfall, and underestimated the precipitation. Thus, the forecast provided by JMA has difficulty forecasting heavy rainfall in our example. It can be said that developing a forecast method for urban heavy rainfall is an important topic.

4. DEVELOPMENT OF FORECAST TECHNIQUE FOR URBAN HEAVY RAINFALL

(1) A simple method suitable for early warning

We developed a simple method suitable for early warning based on an index. Here, we extracted common terms in urban heavy rainfall in the Kinki region, and developed an index that represents the characteristics associated with urban heavy rainfall in Osaka: (a) temperature in the urban areas of Osaka is high and the condition is unstable, (b) wind convergence occurs in urban areas of Osaka, and (c) precipitation areas are present in the south and east areas, and cold air outflow flows in. Considering these characteristics, we found out that the following indices are satisfied in 13 cases of urban heavy falls.

(C1) Temperature of urban areas in Osaka is 29°C or higher

(C2) K index of urban areas in Osaka is 32 or higher

(C3) Air inflow of urban areas in Osaka is 7.0 × 105 kg/s or higher

(C4) Precipitation of 2 mm or more in 10 minutes in the south and east parts of Osaka.

Here, for the temperature in urban areas in Osaka,
we chose whichever was higher between Osaka and Sakai in AMeDAS. The K index was obtained using the initial time of MSM reported at 9:00. For air inflow, the weight of air inflowing to urban areas in Osaka was obtained from AMeDAS interpolated values from the previous section using:

\[
\text{DivAir} = \int \rho \hat{n} dS
\]  

(2)

Here, \(\rho\) is air density and \(\hat{n}\) is the normal vector for area element \(dS\). For these four conditions, 13 cases of urban heavy rainfall in Osaka were summarized (Table 1). The shaded rows indicate cases in which rain of 50 mm/hour or heavier were recorded in the AMeDAS point (Osaka or Sakai). Time (Index) on the right column shows the difference between the time that satisfied these four conditions and the time of heaviest urban rainfall. Time (VSRF) is the difference between the time for urban heavy rainfall forecasted by the VSRF and the time for the heaviest rainfall in urban heavy rainfall. As the heaviest rainfall time for the urban rainfall, the time for the maximum value in the R/A (30-minute interval) was used. Here, (–) means that VSRF could not forecast 25 mm/hour or higher rainfall in urban areas of Osaka. From the table, we can see that in all cases, four conditions were met before urban heavy rainfall started. From these, 11 cases forecasted urban heavy rainfall at least one hour before. In the VSRF provided by JMA, only five out of 13 cases were forecasted. Considering that, the forecast using our index is effective. The reason VSRF was unable to forecast urban heavy rainfall was that it could not take into consideration the effects of wind convergence due to air inflow and instability. We calculated the index for all the days during summer in 2010 to 2012. Results showed that 29 days met the conditions for urban heavy rainfall. Out of those 29 days, urban heavy rainfall actually developed in 13 days as shown in Table 1.

Thus, forecast is possible at the threat score of 45%, false rate of 55%, and miss rate of 0%. In three cases where rain of 50 mm or higher was observed (shaded rows in the Table), temperature was 32°C or higher and K index was 35 or higher, meaning the atmospheric condition was more unstable. If the conditions were changed to temperature of 32°C or higher and K index of 35 or higher, only seven cases over three years met the conditions, and in five of those, urban heavy rainfall occurred. On the other hand, there were cases where heavy rainfall did not occur even though it was forecasted with our index. In these cases, there was precipitation in urban areas of Osaka, but it did not reach 25 mm/hr. Further research is needed for these cases.

Table 1 Index value and forecast time for each case.

<table>
<thead>
<tr>
<th>Case</th>
<th>C1 (deg)</th>
<th>C2 (°)</th>
<th>C3 (10^3 kg/s)</th>
<th>C4 (mm)</th>
<th>Time (index)</th>
<th>Time (VSRF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20100707</td>
<td>29.2</td>
<td>37.9</td>
<td>805</td>
<td>17.2</td>
<td>-2.10</td>
<td>-</td>
</tr>
<tr>
<td>20100803</td>
<td>35.2</td>
<td>34.0</td>
<td>814</td>
<td>2.0</td>
<td>-2.40</td>
<td>-1.30</td>
</tr>
<tr>
<td>20100809</td>
<td>34.3</td>
<td>37.7</td>
<td>713</td>
<td>8.9</td>
<td>-2.40</td>
<td>-</td>
</tr>
<tr>
<td>20110805</td>
<td>31.5</td>
<td>37.4</td>
<td>710</td>
<td>13.1</td>
<td>-2.10</td>
<td>-</td>
</tr>
<tr>
<td>20110827</td>
<td>33.9</td>
<td>35.1</td>
<td>810</td>
<td>2.6</td>
<td>-3.30</td>
<td>-1.30</td>
</tr>
<tr>
<td>20120721</td>
<td>31.2</td>
<td>33.1</td>
<td>846</td>
<td>5.7</td>
<td>-0.40</td>
<td>-</td>
</tr>
<tr>
<td>20120818</td>
<td>34.3</td>
<td>40.1</td>
<td>789</td>
<td>5.6</td>
<td>-2.10</td>
<td>-1.00</td>
</tr>
<tr>
<td>20120819</td>
<td>32.3</td>
<td>35.3</td>
<td>1391</td>
<td>4.4</td>
<td>-1.20</td>
<td>-1.30</td>
</tr>
<tr>
<td>20120824</td>
<td>31.8</td>
<td>33.1</td>
<td>919</td>
<td>5.0</td>
<td>-1.00</td>
<td>-</td>
</tr>
<tr>
<td>20120901</td>
<td>30.3</td>
<td>35.0</td>
<td>859</td>
<td>15.5</td>
<td>-0.20</td>
<td>-</td>
</tr>
<tr>
<td>20120903</td>
<td>32.4</td>
<td>33.0</td>
<td>759</td>
<td>4.3</td>
<td>-1.30</td>
<td>-</td>
</tr>
<tr>
<td>20120914</td>
<td>32.8</td>
<td>36.1</td>
<td>884</td>
<td>15.6</td>
<td>-2.40</td>
<td>-2.30</td>
</tr>
<tr>
<td>20120915</td>
<td>31.8</td>
<td>33.7</td>
<td>732</td>
<td>4.0</td>
<td>-3.50</td>
<td>-</td>
</tr>
</tbody>
</table>

Shaded rows are cases in which rain of 50 mm/hour or more was observed.

(2) Method using numerical weather prediction model

Forecast accuracy of the numerical weather prediction model depends on the accuracy of 3D distribution of initial cloud and wind. However, in the current MSM, X–MP is not being used. Thus, in our research, by assimilating reflectivity and radial velocity of X–MP, and GPS precipitable water, we aim to improve forecast accuracy of the numerical weather prediction model. For the numerical weather prediction model, the Weather Research and Forecasting (WRF) Model was used. Outer domain was defined as horizontal grid of 3 km interval, and inner domain was defined as 1 km interval, to run a one-way nesting (Fig.5). At first, we forecast 1 hour with MSM as the initial value, and reflectivity and radial velocity of X-MP are assimilated to this forecast value to run further 1 hour forecast. This cycle is repeated to prepare the initial values in order to improve the accuracy of forecast. For the assimilation of X-MP, data from the observation sites in Fig.5 were used. Radar observation values of reflectivity and radial velocity at each elevation scan for 5 minutes before the assimilation time were compiled for the grid point value of 1 km interval for assimilation. In this way, we can assimilate higher and more

Fig.5 Computation domain.
detailed density than that of JMA. At this point, quality control was conducted in the same manner as in Xiao et al.\(^6\): (a) removal of data at 10 dbZ or lower, (b) removal of data with high standard deviation, (c) removal of data where reflectivity of adjacent grid points were all 10 dbZ or lower, and (d) removal of grand clutter data. For reflectivity \(Z\) of X-MP, we used \(Z\) that was subjected to rain attenuation correction using the differential phase\(^7\), and was also applied to the C band radar:

\[
Z = 43.1 + 17.5 \log (\rho q_r) \tag{3}
\]

where \(\rho\) is air density and \(q_r\) is mass mixing ratio of raindrops. As in Iwabuchi\(^8\), we used GEONET-data-analyzed GPS precipitable water. Background error covariance matrix was estimated with the NMC (National Meteorological Center) method (Parrish et al.\(^9\)).

Calculation results with August 27, 2011, 13:00 as the initial value are shown in Fig.6 for both assimilated and non-assimilated cases. At this time, 73.0 mm/hour heavy rainfall was observed in Osaka at 16:00, and 53.5 mm/hour heavy rainfall was observed in Miki, Hyogo (Fig.2) at 18:00. Without assimilation, barely any rainfall was calculated for urban areas of Osaka for 16:00 at 4.3 mm/hour. Rain was underestimated for urban areas of Hyogo as well at 18:00, as it was 7.5 mm/hour for Miki. On the other hand, with assimilation, a band of precipitation stretching north–south in urban areas of Osaka was reproduced, and rain was forecasted at 43.1 mm/hour in Osaka at 16:00 and 40.4 mm/hour in Miki at 18:00. This is likely the improved reproduction accuracy of 3D distribution of wind and cloud at the initial time. Precipitation distribution around Osaka at 15:00 and 16:00 in the assimilated case and a vertical cross-section through Osaka at 15:00 are shown in Fig.7. In Osaka, barely any rain was calculated at 15:00. But the wind blew from the rainy area in the southeast, and there was a convergence between the west wind from Osaka Bay and the east wind from Ise Bay. Looking at the vertical cross-section through Osaka, cold air outflow flows into Osaka from the southeast, and it converged around Osaka to create an upward flow. At 16:00, rain of 43.1 mm/hour was calculated for Osaka. By the convergence of cold air outflow, west wind from Osaka Bay, and east wind from Ise Bay, the condition of strengthened rain was repro-

![Fig.6](image_url)

**Fig.6** Forecast precipitation on August 27, 2011 (top: no assimilation, bottom: assimilation).

![Fig.7](image_url)

**Fig.7** Precipitation distribution and vertical cross-section before and after urban heavy rainfall (top: precipitation distribution at 15:00 and 16:00, bottom: vertical cross-section at 15:00).
duced. Such conditions seen in Osaka were not reproduced when there was no assimilation; thus, by assimilating, reproduction accuracy was improved. These results indicate that WRF reproduced the mechanism of local heavy rainfall caused by strengthened convergence of cold air outflow generated in Osaka by assimilating X-MP and GPS precipitable water. It is believed that this method is able to forecast urban heavy rainfall in Osaka.

Next, in the other 12 cases, X-MP and GPS precipitable water were assimilated to WRF in the same manner for the calculation (WRF assimilation), and the results were compared to VSRF and MSM forecasts published by JMA. Initial time of each calculation was set at three hours before the occurrence of urban heavy rainfall. Calculation time was six hours, the same as for the VSRF, and R/A was used for comparison and set as maximum hourly precipitation amount in urban areas of Osaka during the calculation period. The reason we chose the maximum hourly precipitation amount was to evaluate the forecast accuracy while allowing the time lag. The reason we chose the maximum for the urban areas of Osaka was to evaluate the forecast accuracy while allowing positional deviation in Osaka plain where urban areas are concentrated. Considering the fact that transmission of MSM takes two hours and 30 minutes, we chose the newest MSM calculation results that can be obtained three hours before urban heavy rainfall as the comparison target.

Comparison of hourly precipitation amount with each forecast method is shown in Fig.8. With the VSRF, in all cases, precipitation was underestimated, and urban heavy rainfall was not forecasted. This is because VSRF cannot express newly developing rainy areas and growth of cloud; thus, is unable to forecast urban heavy rainfall that builds up and intensifies rapidly. In the two cases where precipitation was heavy, MSM forecasted, though underestimated, urban heavy rainfall. But in other cases, heavy rain was not reproduced. In the case of the August 27, 2011 forecast, time lag was present as shown in Fig.4. The reasons for this may be: (1) a detailed presentation of urban heavy rainfall is not possible due to a large interval of grids, and (2) the generation environment of urban heavy rainfall cannot be reproduced because the accuracy at the initial time is insufficient. On the other hand, calculation results with the assimilation of WRF forecasted urban heavy rainfalls in the two cases with heavy precipitation, and forecasted the amount of rain closer to the observation amount than that of the MSM. In these two cases, there was no time shift for the peak time. In other cases, WRF-assimilated forecasts were closer to the observation precipitation results. In addition, when each case is averaged, VSRF and MSM only forecasted rain of 10 mm/hour or under, but when WRF assimilation was done, rain of 25.8 mm/hour was forecasted, and forecast accuracy of urban heavy rainfall could be said to be much higher. Reasons for this may be: (a) by assimilating X-MP, the accuracy at the initial time was improved, and (b) grid size was small enough that local heavy rainfall was being expressed. However, even when WRF was assimilated, rain falling in the south and east areas along the mountains did not enter the city of Osaka, and heavy rainfall was not forecasted in some cases. In addition, in some cases, peak time was shifted by one to two hours. This is likely because the re-creation of wind distribution such as the convergence field in the initial time was not sufficient.

5. CONCLUSION

In this research, with the aim of forecasting local heavy rainfall in urban areas, we developed the following methods: a simple method suited for early warning, and a method that uses a numerical weather prediction model. Obtained results are as follows: (i) with the simple method that was suited for early warning, urban heavy rainfall in Osaka was not missed and was forecasted at 45% probability. Also, in cases that had especially severe damage, by changing the threshold of the index, forecast accuracy could be improved even more; (ii) in the method that uses a numerical weather prediction model, by assimilating X-MP and GPS precipitable water to WRF, urban heavy rainfall could be reproduced with higher precision than those by VSRF and MSM forecasts.

However, this research targets urban areas of Osaka. At the current time, application is limited to urban areas of Osaka. With the method that uses the numerical weather prediction model, there were
cases that could not be reproduced even with assimilation. This is likely because of insufficient accuracy at the initial time. In the future, efforts to expand into other areas, and use of ensemble method that considers the uncertainty of forecast, and furthermore, advanced assimilation method should be investigated.

ACKNOWLEDGMENT: Observation values of X-MP were provided as part of the research consortium activities by the MILT Water Management and Land Conservation Divisions. We would like to express our deep gratitude to them.

REFERENCES

(Received March 30, 2015)