Composite rainfall map from C-band conventioal and X-band dual-polarimetric radars for the whole of Japan

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1. Introduction

In recent years, localized torrential rainfall has occured frequently during the summer season in Japan. On 28 July 2008, five people (including three children) were killed in a flash flood on the Toga River, Kobe City. Eight days later, five sewer workers in Tokyo died when the area in which they were working was hit by localized torrential rainfall. Since then, the phrase "Guerrilla Heavy Rainfall", coined by the mass media, has become commonplace in Japan, and was awarded the grand prize in the annual buzzwords-of-the-year contest for 2008. Statistical records show that annually, the numbers of days with diurnal precipitation greater than 100 mm and 200 mm have increased over the past century (JMA, 2012). More than 2900 "Guerrilla Heavy Rainfalls" occurred in Japan between 23 July 2013 and 30 September 2013 (WN, 2013). The typical characteristics of such localized torrential rainfall are random occurrence, small horizontal scale, and a short lifetime. Moreover, most catchments in minor urban rivers cover only a few square kilometers to a few tens of square kilometers, and, because most ground surfaces are covered by concrete and pavement, the response of river flow to heavy rain is very rapid, within as little as a few minutes. Hence, to reduce the damage caused by localized torrential rainfall, it is important to compile rainfall maps with high temporal and spatial resolution.

The use of X-band (3-cm-wavelength) radar has several advantages over S-band and C-band radars for purposes of quantitative precipitation estimate (QPE). Shorter wavelengths offer higher sensitivity of the specific differential phase of the rainfall, and enable finer spatial resolution at a lower cost. In addition, because X-band radar can achieve the same beam width with a much smaller parabolic antenna as compared with longer wavelength radar, X-band radar data are more readily obtained in urban and mountainous areas. In Japan, in response to the successful detection of a torrential rainfall event that occurred in Tokyo in 2008 (Hirano and Maki, 2010; Kato and Maki, 2009), the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) established an X-band dual-polarimetric radar network (XRAIN), employing an operational data processing system developed by the National Research Institute for Earth Science and Disaster Prevention (NIED) (Maki et al., 2005a,b; Park et al., 2005). The number of XRAIN stations had increased to 38 by July 2014, covering most of the major cities in Japan, and producing 250×250-m resolution rainfall maps at 1-minute intervals. Figure 1 shows the XRAIN network distribution and coverage.

Although X-band polarimetric radar can improve the temporal and spatial resolution of rainfall observations, the methodology has some disadvantages. First, the detection range of X-band radar is limited to 80 km, which is shorter than that of C-band and S-band radars, whose typical range is 200–300 km and 460 km, respectively. Second, a signal extinction area, which is defined as the area in which the received signal is less than the receiver noise level, tends to appear behind heavy rainfall areas. Moreover, these disadvantages are accentuated during extremely heavy rainfall events. Hence, the present paper reports on a method to generate a composite rainfall map for the whole all Japan based on a combined X-band and C-band radar-observation dataset, so as to minimize the limitations described above.

2. Data processing and composition method

The X-band dual-polarimetric radar QPE has been shown to be comparable to that of rain gauge observations, in places without signal extinction. Kim and Maki (Kim and Maki, 2012) validated the composite map of radar parameters and rainfall amounts using data from four X-band dual-polarimetric radars around Tokyo, and demonstrated that the multiple radar observation process can effectively compensate for the extinction area. The XRAIN system delivers high-accuracy rainfall estimations at 1-minute intervals, at a spatial resolution of 250×250 m, and implements the following protocols to overcome the disadvantages of X-band radar (Maesaka et al., 2011).

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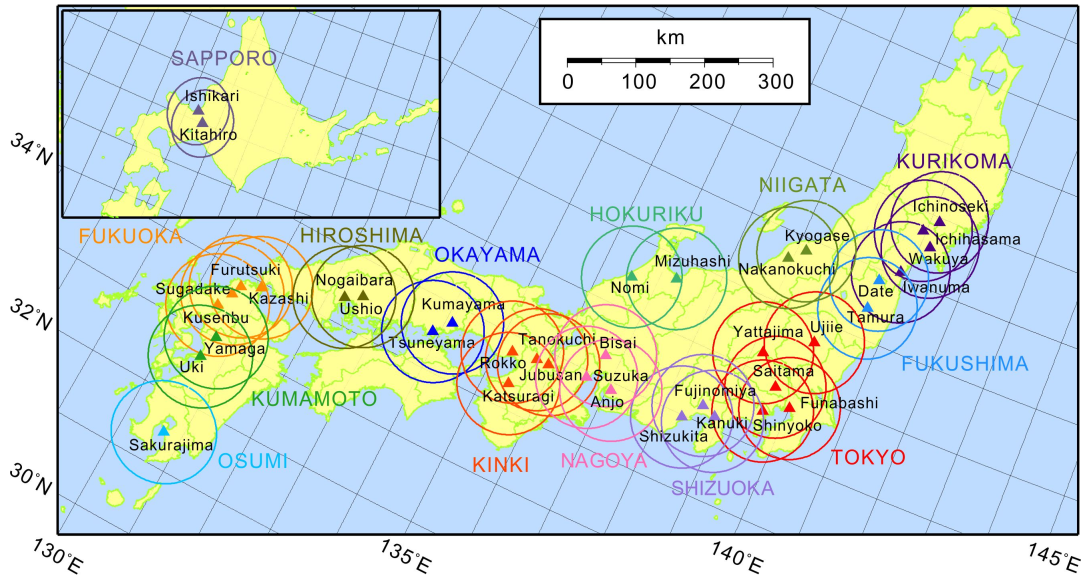

Figure 1: Radar distribution and coverage by XRAIN. Triangles show the radar locations (with names in black letters). Circles around each triangle have a radius equivalent to 80 km, and indicate the detection ranges of the radars. The colors of triangular and circular radar symbols identify the radars in specific areas. The geographical names of the areas are expressed in upper case bold letters using the same color as that of the radar symbols.

- Coverage of the target observation area by multiple radars; 14 target areas are designated (see Fig. 1), classified as either densely inhabited areas, landslide-prone areas, or volcano monitoring areas.
- Each radar covering a target observation area is within a range of 30 km, and adopts a beam-blocking and point-cluttering protocol to mitigate the effects of complex terrain or artificial structures.
- Installation of numerous quality control checks in the system to eliminate noise, clutter, and non-meteorological echoes, including geographical masking, close-range elimination, SNR checks, calibration of received power, ground clutter removal, unfolding and texture parameterization of Φ_{DP}, threshold of ρ_{HV} and K_{DP}, and Z_{DR} filtering.
- Two-step attenuation corrections to ensure the quality of horizontal reflectivity (Z_h).
- Use of composite estimators of $K_{DP} - R$ and $Z_h - R$ relationships to estimate rainfall intensity.
- Identification of signal extinction areas using a detection threshold.

In addition to XRAIN, the Japan Meteorological Agency (JMA) operates a network of 20 C-band doppler radars covering the whole of Japan, for observing the distribution of rainfall intensity. Up to now, JMA has revised its radar-observed rainfall distribution map using measurements from a surface raingauge network named the Automated Meteorological Data Acquisition System, (AMeDAS), which has an average spacing between stations of 17 km. A radar-echo map is generated every 5 minutes by merging all radar data, and a QPE product based on the radar AMeDAS-analyzed precipitation map is issued every 30 minutes, showing cumulative hourly rainfall amounts at a spatial resolution of 1×1 km.

The new QPE product described in this paper aims to provide data for hydrological applications, at a resolution and response time applicable to those of localized torrential rainfall events. The approach is based on a combination of XRAIN and JMA radar-echo maps. Because rainfall intensity is updated every 1 minute by XRAIN, and every 5 minutes by JMA, the QPE product is generated by two processes. At 5-minute intervals, upon release of a new JMA product, the 1-km mesh JMA radar-echo is remapped to the XRAIN grid, first using a bilinear interpolation. Then, a composite rainfall map is generated using the following procedure (Kato et al., 2012):

$$R_{JMA-COR} = \beta R_{JMA}, \quad where \ \ E(R_{XRAIN}|R_{JMA}) = \beta R_{JMA} \tag{2.1}$$

$$R_{COMP} = \begin{cases} R_{XRAIN}, & (R_{XRAIN} \geq c) \\ R_{JMA-COR}, & (R_{XRAIN} < c) \end{cases} \tag{2.2}$$

where R_{JMA}, R_{XRAIN}, $R_{JMA-COR}$, and R_{COMP} are rainfall intensities of remapped JMA, XRAIN, corrected R_{JMA}, and the composite map product, respectively, and c is the rainfall intensity threshold, which can be easily modified by users. The conditional expectation is approximated using data at grid nodes where rainfall intensity recorded by XRAIN is greater than zero. For the time steps between the 5-minute intervals, when no JMA data are available, the JMA rainfall is interpolated from the JMA radar-echo map at boundary conditions using a weighting coefficient that is proportional to the time interval, according to

$$R_{JMAt-i} = (t-i)R_{JMAt-5} + (i)R_{JMAt}, \quad where \;\; i \in (1,\ 2,\ 3,\ 4) \tag{2.3}$$

After estimating JMA rainfall data at each XRAIN time step, the composition procedures shown in equations (2.1) and (2.2) are repeated. As a consequence, the composite rainfall map is released at time intervals of 5 minutes, but include 1-minute-resolution rainfall intensity data for the whole of Japan. In addition, the cumulative rainfall amounts based on rainfall intensity are added to the dataset for use in hydrologic applications.

3. Results

The composite rainfall map (MP-JMA) product shows rainfall intensity (RR) at a time resolution of 1 minute and a spatial resolution of 250 × 250 m. The cumulative information is recorded every 5 minutes, including rainfall amounts in the previous 5 minutes (R5M), previous 1 hour (R60M), previous 3 hours (R180M), and previous 24 hours (R24H), and effective rainfall for the previous 1.5 hours (ER90M) and 72 hours (ER72H), which is considered important for predicting debris flows and slope failures. The system operates in real time, and covers the whole of Japan. Figure 2 shows the rainfall intensity distribution estimated by the XRAIN, JMA, and MP-JMA products at 1800 UTC on 13 August 2012.

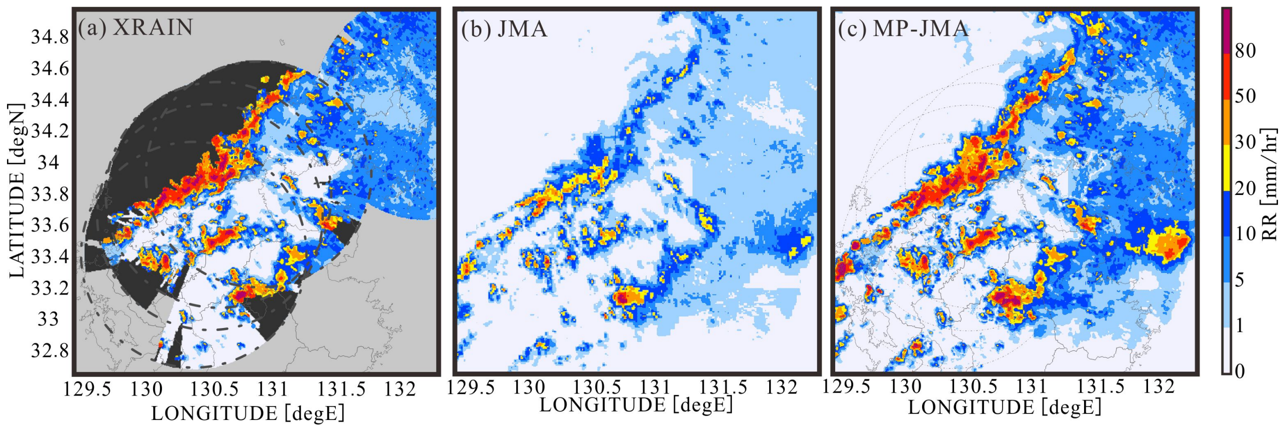

Figure 2: Example of composite rainfall intensity map at 18:00, 13 August 2012 (UTC) in Fukuoka area. (a) shows XRAIN rainfall intensity, (b) shows JMA radar-echo map, and (c) is the composite rainfall map. The gray dotted circle denotes the detection range of each X-band radar in (a) and (c). The black area in (a) denotes the signal extinction area.

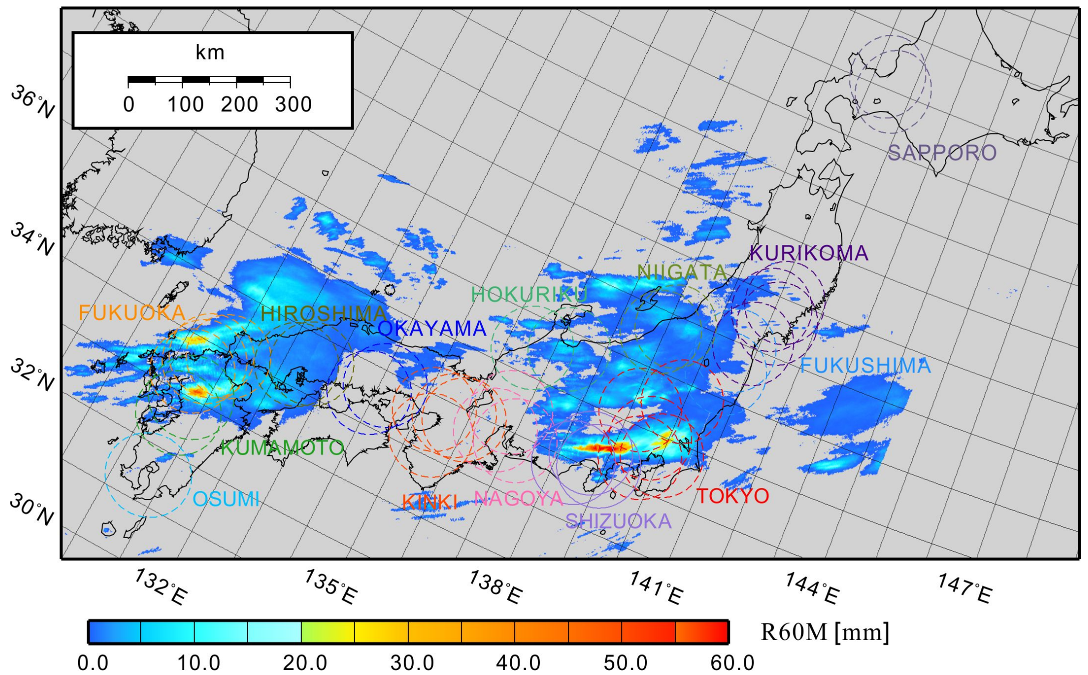

Figure 3: Cumulative one hour rainfall amount (R60M) at 18:00, 13 August 2012 (UTC). Circles and capital letters denote the same meanings as in Fig.1

The XRAIN product is able to detect rainfall at higher resolutions and with higher accuracies than is the JMA product, but the signal extinction (shown by the black area in Fig. 2(a)) behind the heavy rainfall field is large. In contrast, the JMA product gives results for the entire grid, but rainfall is underestimated in heavy rainfall areas. The MP-JMA product has the advantages of both the XRAIN and JMA products; although some artifacts appear at the boundaries of the two sets of data, the data quality is acceptable for hydrologic applications, such as for estimating total basin rainfall amounts and providing inputs for precipitation nowcasting models.

River flood control, sewer management, and dam construction all rely on rainfall accumulation data, and to provide data for these various purposes, the accumulations over multiple time spans are recorded. One example of the application of cumulative rainfall amounts in a composite rainfall map product is shown in Fig. 3. The parameter is R60M, which is calculated by summing the previous 60 rainfall intensities and dividing by the time (60 minutes). For verification of R60M, values were compared with rain gauge measurements (not shown here), yielding a correlation between the two datasets of 0.79 and a root mean square error of 10 mm. This error is acceptable for estimations of hourly rainfall amounts.

4. Summary and Conclusion

This paper presents a technique for obtaining a highly accurate and seamless real-time rainfall map using composite X-band dual-polarimetric radar observations (XRAIN) and C-band doppler radar observations (JMA) for the whole of Japan. The composite rainfall intensity map is generated at a time resolution of 1 minute and a spatial resolution of 250 $\times$ 250 m. The composite rainfall amount map has a time resolution of 5 minutes and includes six rainfall amount parameters (10-minute accumulation, 60-minute accumulation, 180-minute accumulation, 24-hour accumulation, 90-minute effective rainfall, and 72-hour effective rainfall). The XRAIN product is accurate for relatively heavy rainfall events, but suffers from strong signal extinction behind the heavy rainfall field. On the other hand, the accuracy of the JMA product is good under conditions of relatively weak rainfall, but the product generally underestimates heavy rainfall. The composite rainfall map makes use of the advantages of each radar dataset, and is well correlated with raingauge measurements.

The 5-minute-updated composite rainfall map can be accessed online on a trial basis, at `http://mpsep2.bosai.go.jp/webmain/mapmain.htm`. However, access is currently password protected and the content is presented in Japanese only. We conclude that the composite rainfall map of X-band and C-band radar observations provides accurate information about rainfall intensity distributions, and such maps are useful for various hydrological applications.

Although the composite rainfall map is more accurate than the XRAIN and JMA products alone, the average bias compared with rain gauge measurements is less than 1, which indicates a degree of underestimation. The inaccuracies can be very high when the rainfall intensity is extremely high; for example, in cases of rainfall intensity greater than 100 mm/hr. Hence, future work should focus on the statistical validation of composite rainfall maps to obtain non-biased rainfall data.

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