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Analyzing the heavy rainfall event of July 2011 in Niigata using ground, satellite and radar rainfalls

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सार– हाल के वर्षों में रेडार और उपग्रह वर्षण प्रेक्षणों का अनुप्रयोग खराब तरीके से मापित क्षेत्रों के लिए तेजी से उपयोगी हो गया है। हालांकि, इन डेटा स्रोतों और जमीनी प्रेक्षणों के बीच संबंधों को समझना डेटासेट को सही करने और जल विज्ञान अध्ययनों में उनके अनुप्रयोग को बेहतर बनाने के लिए महत्वपूर्ण है। इस अध्ययन में हमने जापान में शिनानो नदी के बहाव में रेडार और जमीनी प्रेक्षणों के साथ ग्लोबल सैटेलाइट मैपिंग ऑफ प्रेसिपिटेशन-नियर रियल टाइम (GSMaP_NRT) डेटा सेट के बीच स्थानिक और कालिक संबंधों का विश्लेषण किया। GSMap_NRT प्रेक्षण ने प्रति घंटे के प्रेक्षण की तुलना में लंबी अवधि के प्रेक्षणों (जैसे 3, 6, 12 और 18 घंटे) के लिए जमीनी प्रेक्षणों के साथ बेहतर संबंध दिखाया। GSMap_NRT ने अप्रेक्षणित समय की तुलना में उपग्रह प्रेक्षण समय पर जमीनी वर्षा के साथ उत्कृष्ट संबंध दिखाया। विभिन्न समय पैमानों और स्थानिक विभेदनों पर रेडार प्रेक्षणों की तुलना से पता चला कि छोटे-समय-अंतराल अनुपात और निम्न-स्थानिक-पैमाने के अनुपात पर रेडार अनुमान लंबे-समय-अंतराल अनुपात और उच्च-स्थानिक-पैमाने के अनुपात से बेहतर है। यह भी देखा कि रेडार वर्षण अनुमान जमीनी प्रेक्षणों के क्षेत्रीय औसत वर्षण का अच्छी तरह से प्रतिनिधित्व करते हैं। इस अध्ययन के परिणामों से पता चला है कि रेडार वर्षण अनुमान जमीनी और उपग्रह वर्षण के विलय के साथ-साथ उपग्रह वर्षा सुधार प्रणालियों को बेहतर बनाने के लिए बहुत महत्वपूर्ण इनपुट के रूप में काम कर सकते हैं।

ABSTRACT. In recent years the application of radar and satellite precipitation observations has become increasingly useful in poorly gauged areas. However, understanding the relationships between these data sources and ground observations is vital to correct the datasets and improve their application in hydrological studies. In this study we analyzed the spatial and temporal relationships between Global Satellite Mapping of Precipitation-Near Real Time (GSMaP_NRT) data set with radar and ground observations at downstream of Shinano River, Japan. GSMap_NRT observation showed better relationship with ground observations for longer-duration observations (*e.g.* 3, 6, 12 and 18 hours) than hourly observations. The GSMap_NRT showed excellent relationship with ground rainfall at satellite observation time compared to non-observation time. Comparison of radar observations at various time scales and spatial resolutions showed that radar estimates at smaller-time-interval ratio and lower-spatial-scale ratio are better than longer-time-interval ratio and higher-spatial-scale ratio. We also observed that radar precipitation estimate well-represent the areal averaged precipitation of ground observations. Results from this study showed that radar precipitation estimates could serve as very important input to improve merging of ground and satellite precipitation as well satellite rainfall improvement systems.

Key words – GSMaP_NRT, Shinano River, Ground, Satellite, Radar, Rainfall.

1. Introduction

Precipitation is one of the crucial parameters of the hydrological cycle on a river basin scale. Precipitation data are of utmost importance to carry out many hydro-meteorological analyses. Since a ground-based raingauge represents only a point (very small area) rainfall amount, we usually establish a network of multiple raingauges enough to get areal rainfall distribution and amount on a river basin scale. However, due to financial and/or technical constraints, poor implementation of raingauges and/or maintenance have created uncertainties in measurement and processing of precipitation on the ground. In this context, satellite-based rainfall estimation (SRE) and ground-based radar-derived rainfall estimation (RRE) could be alternative options for areal rainfall estimation.

One of the important characteristics of SRE is its comprehensive coverage and relatively uniform resolution on a global scale. The RRE is also available in spatially distributed manner but they do not cover a wide area compared to SRE. In a poorly-gauged river basin without enough raingauges and any radar, SRE is precious hydrological data. It is, therefore, quite a natural approach to find a decent merge method of GR and SRE in order to optimum use of the both data sets. It is a fact that ground rainfall data is a point value and SRE is availed in spatially distributed condition. One of the limitations of a network of GR stations and RRE is their establishment and operation cost for rainfall monitoring organization. Therefore, merging of GR and SRE could be an effective way to provide good quality rainfall data without extra financial burden.

Prior to developing a merging method of those data or correction methods of SRE, it is necessary to grasp the difference of the characteristics between these three types of data (SRE, RRE and GR). The factors of differences between these data are summarized in the following three points. The first factor is the algorithm of estimation of rainfall intensity from the passive microwave sensor (radiometer) which includes the classification of rainfall type, estimation of background emission over the earth surface, *etc*. Aonashi *et al.*, 2008 studied the precipitation retrieval algorithm of a SRE, the global satellite mapping of precipitation (GSMaP) of Japan Aerospace Exploration Agency (JAXA). They found that in land areas, GSMaP underestimated the precipitation rates more than 10 mm/h whereas it overestimated the precipitation less than 10 mm/h in the ocean. Kubota *et al*., 2009 reported that the accuracy of GSMaP over mountainous areas is lower than that of ocean area. Although they are thought to be inherent discussions about the characteristics and/or their causes, they are not discussed in this paper because we focus on the observed characteristics for the target area.

The second factor is the frequency of polar-orbit satellite observation with microwave radiometer. Polar-orbit satellites keep on moving over the globe so that continuous rainfall observation at any specific point is impossible. Rainfall observation from microwave sensors aboard several satellites can be made only when they pass over the target area. Only one snapshot may be used to estimate hourly rainfall intensity at a pixel. The rainfall event which occurs between the observations cannot be caught by satellite. Ozawa *et al.,* 2011 studied the characteristics of GSMaP_NRT and the application of a self-correction algorithm modified from Shiraishi *et al*., 2009, using the data for the typhoon "Morakot" in 2009 in Taiwan. They found the modified self-correction algorithm worked well but the accuracy of self-corrected satellite-based rainfall data was greatly affected by the timing of real observations from satellites and concluded that more frequent observation was needed to improve the accuracy of GSMaP_NRT.

The third factor is spatial and temporal resolution of rainfall data. In terms of spatial resolution, satellite rainfall data represent instantaneous rainfall intensity averaged over the area of 100 km^2 area in case of GSMaP_NRT whereas RRE represents 1 to 5 minute rainfall intensity over the area of 0.01 to 1 km^2 and GR represents one-hour accumulated value at a single point. A direct comparison of 100 km^2 averaged rainfall data with the accumulated point value is expected to have bias due to the resample problem.

Therefore, the objective of this study is to identify the characteristics of SRE and its difference from RRE and GR and their response in a heavy rainfall event. This study has indicated pros and cons of each rainfall product which is a preliminary study on SRE before starting a study on merging SRE with GR and/or on correcting SRE.

In this paper, the MLIT's (Ministry of Land, Infrastructure, Transport and Tourism, MLIT) C-band radar data are used to find out the basic characteristics between accumulated point data and instant snapshot of rainfall distribution. The RRE by the MLIT C-band radars is based on converting the reflectivity (Z) of the radar signal, which records backscattering by raindrops, into rainfall estimates (R) through a non-linear power function (Tesfagiorgis *et al*., 2011). The RREs are spatially distributed and they are generally affected by beam blockage especially due to mountainous areas. It is a fact that the accuracy of RRE and SRE depends on the calibration procedure used, the seasons and the geographic location (Yilmaz *et al*., 2005). The fine spatial resolutions and high frequency of C-band radar observation enable us to make data set similar to accumulated point value and instant but spatial value. The statistical tendencies between different time scale and space resolutions are investigated in this paper.

In this regard, we pursued this study and we identified satellite-radar rainfall relationships which may be significantly helpful to carry out rainfall improvement mechanisms such as merging of ground and satellite rainfalls. The results of investigation can possibly be feedback to existing works to investigate the accuracy of the satellite rainfall data.

2. Study area and data

This study has been carried out downstream of the Shinano River basin of Japan. Shinano River originates from the Kanto Mountains, Mt. Yatsugataka and the Hida range and links various basins as it reaches and crosses the Echigo plain on its way to the Japan sea. The river is located in the central part of Japan having length of 367 kilometer and it is the longest river in Japan. Fig. 1 shows the study area with rain gauge stations.

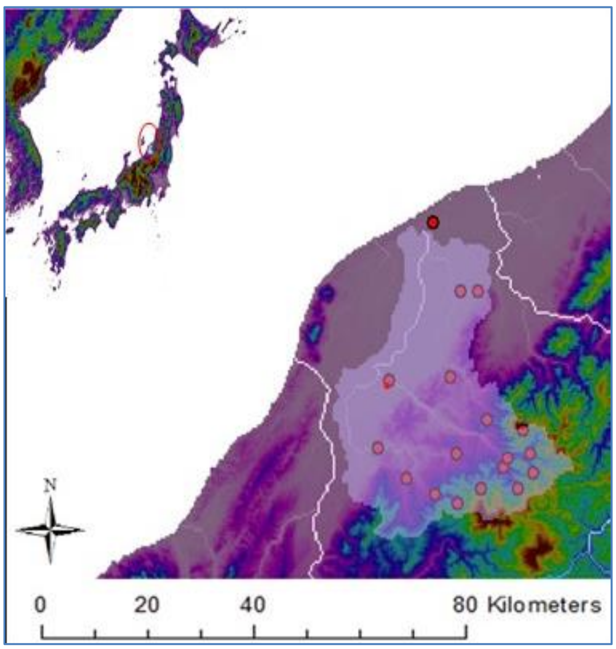

Fig. 1. Study area with rain gauge stations.

We have selected eighteen rain gauge stations in the downstream area of the Shinano River for comparison with the SRE and RRE. These stations are located within an area of 1271 sq. km. that is, 1 rain gauge is approximately within an area of 71 sq. km. This study period is from 27 to 30 July 2011; when a torrential rainfall event occurred. Due to this heavy rainfall, 6 persons were killed, 133 houses were destroyed and 9225 houses were inundated (Ushiyama and Yokomaku, 2012). Among these 18 stations, the maximum ground and satellite rainfall intensities were 93 mm/hour and 38.18 mm/hour at Kasabori and Tochibori stations respectively. Its two-day cumulative areal rainfall in the downstream area was about 390 mm which corresponds to the return period of 150-300 years (Hokuriku Regional Development Bureau, 2011).

We have taken the GSMaP_NRT hourly data from 27 to 30 July 2011 as satellite-based rainfall estimation. The GSMaP_NRT rainfall is one of the popular products in the world which is available within 60^o N to 60^o S and it has spatial and temporal resolutions of 0.1^o and 1 hour respectively (JAXA, 2012).

We have taken the C-band radar rainfall within the latitudes of 37^o 19' 0" to 37 ^{o} 57' 0" and longitudes of 138^o 28' 0" to 139 ^{o} 40' 30". We took cumulated RRE rainfall data of 10 minutes, 20 minutes, 1 hour, 3 hours and 6 hours. Likewise, we resampled the RRE to obtain data sets with different spatial resolutions of 1 km, 2.5 km, 5 km and 10 km, as shown in Table 1 and Table 2.

TABLE 1

Temporal intervals of data set

Case	T05	T10	T20	T60	T180	T360
Time interval	5 min	10 min	20 min	1hr	3 hr	6 hr
Resolution			1 km			

TABLE 2

Spatial resolution of data set

Case	X10	X25	X50	X100
Time interval		5 min		
Resolution	1 km	2.5 km	5 km	10 km

3. Methodology

In principle, ground observed rainfall data, the SRE and RRE are not the same kind of data. GR is accumulated point data whereas the SRE and RRE are mainly obtained by analyzing snapshots. One of the major values associated with SRE and RRE is their spatial distribution. In order to conduct fair comparison between satellite rainfall with ground and radar rainfall, we took basin average values for all the rain data sets. Basin average rainfalls were taken by the Thiessen Polygon method.

Another comparison has been made at satellite observation and non-observation time periods. Statistical analysis between GR and SRE has been performed for all hours, satellite observation and non-observation time periods separately. Cumulative rainfalls for 3 hours, 6 hours, 12 hours and 18 hours of SRE and GR were compared to identify their relationships in different temporal scales. The C-band radar rainfall data are used for comparison with ground and satellite rainfall data sets due to its fine temporal and spatial resolutions. The relationships among RRE with different time interval listed in Table 1 were analyzed. Similarly, correlations between SRE and RRE at different spatial resolutions listed in Table 2 were investigated.

Using the data sets given in Table 1 and Table 2, the relationships between different-time cumulative rainfalls and different resolutions are investigated. Such investigations with different temporal and spatial cases have shown the characteristics of GR, SRE and RRE in the Niigata-Fukushima storm event of July 2011. We applied statistical indices such as correlation (r), mean error (ME), mean absolute error (MAE), root mean square error (RMSE), slope and coefficient of determination (R^2) in order to determine different relationships among GR, SRE and RRE.

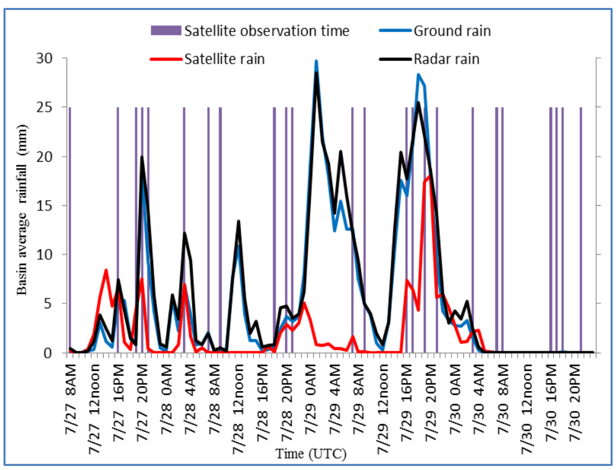

Fig. 2. Basin average rainfall by GR, SRE and RRE with satellite observation time.

4. Results and discussions

4.1. *Analysis of peak rainfalls*

The timeline of basin averaged rainfall with satellite observation time are given in Fig. 2. The Fig. 2 shows that basin average GR and RRE are almost the same throughout the study period. Similar kinds of results are obtained with SRE only when MW observations are made such as July 28, 03:00, 16:00, 20:00, 21:00, July 29, 20:00 and July 30, 00:00.

We analyzed the total rainfall event in three different periods based on the peaks of rainfall intensity as shown in Table 3.

In the first period, rainfall peak occurred in July 27, 20:00 to 21:00. This case is selected as a relatively short duration rainfall event with microwave radiometer (MWR) observation. In the second period, peak occurred between late hours of July 28 to early hours of July 29 and the rainfall event lasted for about 12 hours. This period was selected as a long duration rainfall event with no-MWR observation. In the third rainfall event which lasted for about 9 hours, the peak was seen on 14:00 to 22:00 of July 29. This case was selected as a long duration rainfall event with MWR observation.

TABLE 3

Rainfall periods of interest

Station	Date and time (UTC)
Period 1	2011/7/27/20:00 -2011/7/21:00
Period 2	2011/7/28/22:00-2011/7/29/09:00
Period 3	2011/7/29/14:00-2011/7/29/22:00

TABLE 4

Peak rainfall intensities in the second period

Station	Date and time (UTC)	Ground rain (mm/hr)
Gejyou dam	2011/7/29/1:00	85
Kasabori dam	2011/7/29/1:00	83
Miyayorikami	2011/7/29/1:00	91
Kasabori	2011/7/29/7:00	93

We found from Fig. 2 that the first and the third period rainfalls were observed by satellite while the second period was not frequently observed. During the second period, rainfall was mostly concentrated in South-eastern part of upstream of the Shinano River. It can be justified by the peak rainfall intensities greater than 80 mm/hr within the second period listed in Table 4.

The rain intensity of 93 mm/hr of July 29 at 7:00 is the highest amount of intensity found among these 18 rain gauge stations within 96 hours. When the peak rainfall was found within 13:00 to 22:00 of July 29, rainfall area was widely distributed for longer duration. It can be justified by the rainfall quantities recorded by each station in the basin. However, quantitatively these rain intensities are slightly lower than the rain intensities given in Table 3. It is a reality that such an intense-rainfall for longer duration in the upstream area of Shinano River is one of the major reasons for flooding in the downstream areas. Flooding was enhanced by characteristics of rainfall since intense rainfall had already started before July 29 so that the ground was already saturated which became a major reason to increase surface runoff including river discharge.

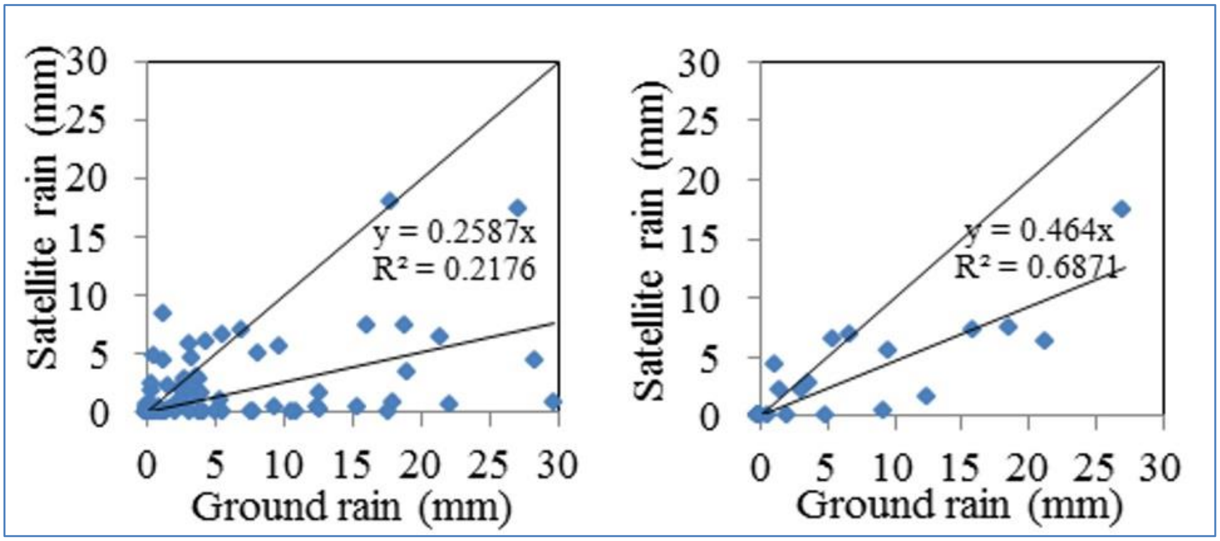

Fig. 3. Ground and satellite rainfall relationships (Left to right: correlation between ground and satellite for all hours and satellite observation times only).

TABLE 5

Correlations between SRE and GR

Statistical tests	For all hours	For satellite observation times only	For Satellite non-observation times only
ME	3.08	**3.06**	3.23
MAE	3.64	**3.47**	3.95
RMSE	6.91	**5.71**	7.43
r	0.49	**0.83**	0.23
R^2	0.22	**0.69**	-0.02
Slope	0.26	**0.46**	0.17

4.2. *Effects of extrapolation of direct measurements from polar-orbit satellites for GSMaP_NRT on the correlation with GR*

GSMaP_NRT extrapolates rainfall intensity for hours without direct observational data of MWR aboard polar-orbit satellites, in combination with the information of the movement of rainfall areas which are acquired from optical images of geostationary satellites. As shown in Fig. 2, direct observation data are very limited and most of SRE are "indirect", *i.e.*, extrapolated data from the previous direct observation data. Therefore, the difference between direct and indirect observations may affect the accuracy of SRE in comparison with GR. Therefore, we analyzed the correlations between SRE and GR, separately for all hours, for satellite observation hours only and for non-observation (extrapolated) hours only. We calculated statistical indices such as correlation (r), mean error (ME), mean absolute error (MAE), root mean square error (RMSE), slope and coefficient of determination (R^2). The results are given in Table 5.

Table 5 clearly shows that ground and original satellite relationship is excellent in satellite observation time compared to satellite non-observation and all time periods. Similar kinds of results are observed through scatter plots which are depicted in Fig. 3. It is found that satellite observations were conducted for 5, 6, 6 and 7 times within July 27 to 30 respectively. It shows satellite observations were performed once 4 hours in average. Analyzing all these results, it is clear that observation frequency affects the accuracy of the SRE.

4.3. *Effects of difference of sampling interval on the correlations between SRE and GR*

We analyzed the relationships of RRE with different time intervals. In this analysis, the relationships between

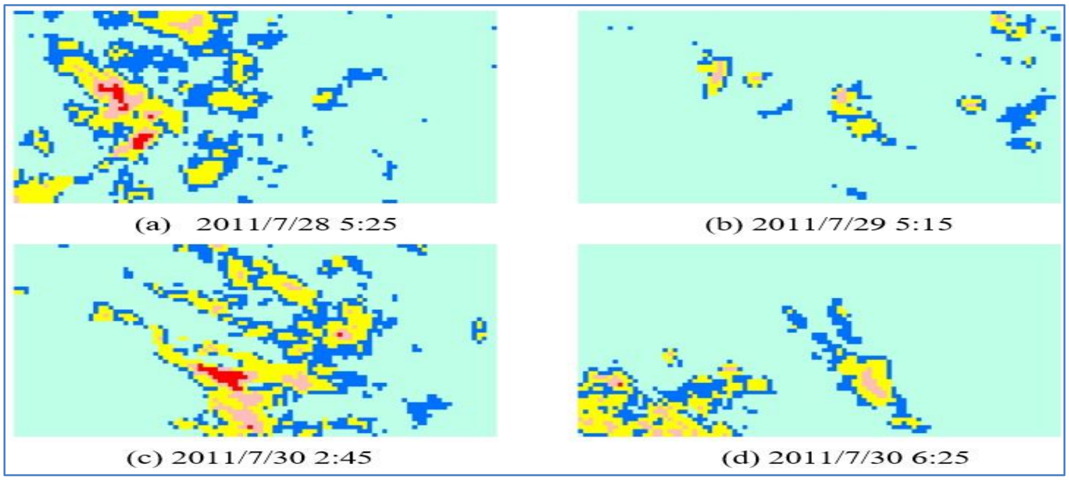

Fig. 4. Snapshots of rainfall area taken by radar at same date and time given in Table 7.

TABLE 6

Temporal relationships of radar rainfall

Date (JST**)	Relationship		Ratio	R^2
(Period 1) 2011/7/28 00:00 to 06:00	T05	T10	2	0.80
		T20	4	0.61
		T60	12	0.33
		T180	36	0.08
		T360	72	0.03
	T60	T180	3	0.24
		T360	6	0.09
	T180	T360	2	0.39
(Period 2) 2011/7/29 06:00 to 12:00	T05	T10	2	0.90
		T20	4	0.80
		T60	12	0.63
		T180	36	0.35
		T360	72	0.16
	T60	T180	3	0.55
		T360	6	0.25
	T180	T360	2	0.46
(Period 3) 2011/7/30 00:00 to 06:00	T05	T10	2	0.89
		T20	4	0.78
		T60	12	0.57
		T180	36	0.37
		T360	72	0.24
	T60	T180	3	0.64
		T360	6	0.42
	T180	T360	2	0.65

**JST means Japanese standard time

all the combinations listed in Table 6 were investigated. Outputs of the analysis are depicted in Table 6 and the date JST is a short form of Japanese Standard Time. Analyzing the results obtained from temporal study, it can be said that RRE sets having shorter time-interval-ratio have shown higher correlation than longer time-interval-ratio which is quite a natural tendency. In this analysis, T05 and T60 show temporal relationship between 5 minutes observation and one hour cumulative rainfall. In the case of the first period, where the time duration of the rainfall event is relatively shorter than the other cases, R^2 values become lower. In the case of second and third periods, where the time duration of rainfall events are 12 and 9 hours respectively, R^2 values become higher. These results indicate that instant observation by SRE can represent one hour rainfall intensity in the case of longer duration rainfall events. Instead, instant observation cannot represent one hour rainfall in the case of shorter duration rainfall events.

4.4. *Effects of spatial resolution*

We identified relationships between different spatial resolutions as 1 km & 10 km, 1 km & 5 km, 1 km & 2.5 km. Results of the analysis are given in Table 7 where the date and time are the exact observation time of MWR. The cases with lower spatial-scale-ratio have higher R^2 values, which is a quite natural tendency. Fig. 4 shows rainfall areas taken by RRE at each date and time listed in Table 7. The result of 29th July 5:15 shows relatively lower R^2 than other date and time. It can be understood that Fig. 4 (b) has a significantly smaller rainfall area compared to other cases. Relating the results of Fig. 4 & Table 7, it can be said that R^2 values for different scale resolutions depend on size of rainfall area. Thus, it is natural to conclude that when the rainfall area is large, the GR and SRE relationships are expected to be high.

It is found that relationships between higher resolutions, for example 1 km and 2.5 km has given better results than coarse resolutions as 1 km and 10 km. Table 7 clearly shows that rainfall distribution will be comparatively improved if we take care of the spatial resolution.

TABLE 7

Comparison of R^2 at different resolutions

Date (JST) (Yr. 2011)	1 km 10 km	1 km 5 km	1 km 2.5 km
7/28/5:25(a)	0.50	0.73	0.89
7/29/5:15(b)	0.30	0.58	0.80
7/30/2:45(c)	0.53	0.70	0.86
7/30/6:25(d)	0.52	0.71	0.87

5. Conclusions

Ground, satellite and radar rainfall relationships were analyzed for the Niigata-Fukushima storm event in July 2011. This study showed that heavy rainfall intensities were underestimated by GSMaP_NRT in most of the cases. Ground-satellite rainfall relationships at longer durations are better than shorter durations.

Satellite-radar relationships were analyzed with respect to temporal and spatial cases. The radar rainfall relationship at 3 hours and 6 hours, 5 minutes and 1 hour are better than 5 minutes and 3 hours and 5 minutes and 6 hours. Comparative studies of the relationships between different resolutions have shown that higher resolution, that is, relationships between 1 km and 2.5 km is better than the relationships between 1 km and 5 km and 1 km and 10 km. In areal analysis, radar rainfall has shown almost similar results with ground rainfall. Thus, radar rainfall data set could be an alternative option to enhance ground-satellite merging.

The ground-satellite correlations were relatively improved for basin-averaged rainfall data at satellite observation time. Hence it can be strongly said that regular satellite observation is one of the solutions to remedy some weaknesses associated with satellite rainfall systems. Since satellite-based rainfall products have high potential of flood forecasting in poorly-gauged river basins, it needs to improve satellite rainfall data systems although we also need to conduct more case studies.

In this study, we found that the time duration and size of rainfall events affect the accuracy of the SRE and GR. In analysis of radar data with different time cumulative data sets, we found that a snapshot of the rainfall observation has less correlation to one hour cumulative rainfall data. It indicates that consistency between the SRE and GR in shorter rainfall events is expected to be less than that of longer duration rainfall events. Likewise, in analysis of radar rainfall with different resolutions, we found that small scale rainfall events are not expected to be captured by large resolution data. It implies that consistency between the SRE and GR is expected to be less in the case of small scale rainfall events. In a nutshell of conclusion, further investigation with a larger number of datasets will be able to identify the various factors which affect the accuracy of the rainfall systems including SREs.

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