Daily quantitative precipitation estimates use weather radar reflectivity in South Sulawesi

Giarno\textsuperscript{1,2}, M P Hadi\textsuperscript{1}, S Suprayogi\textsuperscript{1}, S H Murti\textsuperscript{1}

\textsuperscript{1}Departement of Geography, Faculty of Geography, Gadjah Mada University
\textsuperscript{2}Paotere Maritime Station, BMKG Makassar

giarno@mail.ugm.ac.id

Abstract. Radar reflectivity data are widely used in rainfall estimates for flood warning. The quantitative precipitation estimates (QPE) of the radar take advantage of the relationship of radar reflectivity and rainfall observed. However, the lack of surface rainfall data sites makes the adjustment of temporal radar resolution in 5’ or 10’ cannot be provided in a lot of countries especially in Indonesia. Precipitation data in this region are commonly available in daily accumulation so that it is difficult to directly relationships between the reflectivity of radar and rainfall observed. The aim of this research is to get one method obtaining of daily radar QPE that don't have the same temporal resolution in South Sulawesi, the part of the tropical Indonesian maritime continent. The daily radar’s QPE is done by using the accumulation of radar’s reflectivity on the several radius grids for capture rainfall in a location. Relation of reflectivity-rainfall observed uses linear models and will be evaluated by the root mean square error (RMSE) and correlation. The results show that the daily accumulation of radar reflectivity has the potential for radar's QPE. While the accumulation radar reflectivity on the 0.5000\textdegree grid area is the best choice for rainfall estimates. The evaluation in daily rainfall estimates of the whole area shows that the stronger correlation in a location, the greater the RMSE, both use original reflectivity or interpolation result. Based on QPE in each station shows that the user of larger grid products smaller RMSE in almost all locations. Conversely, the area which has a correlation between 0.0 to 0.2 obtained the smallest RMSE. Meanwhile, the large deviation between model and rainfall observed occurs in the west coast of South Sulawesi. The rainfall fluctuation has an effect on radar’s QPE so that the availability of rainfall data observed with high temporal resolution is still needed in the evaluation.

1. Introduction

Quantitative precipitation estimate (QPE) of radar is important both on measurement and forecasting for some hydrology purposes. But there is a lack of rainfall observation if it follows the standard of the World Meteorological Organization (WMO) of the requirement of rain gauge density [1]. Moreover, in the urban drainage systems require rainfall information on high spatial and temporal resolutions [2-4]. The weather radar provides high-resolution spatial distribution, which very useful to fulfill the lack of rain gauge sites. However, the ability in quantitative precipitation estimated (QPE) is still a concern since of radar’s limitation [5, 6].

The sources error of radar is ground clutter, precipitation variability, air motion, sampling error, and beam blocking [7, 8]. Therefore, QPE of radar may vary at each location, time and distance [9, 10]. Obtained radar’s QPE uses the equation that relates radar’s reflectivity and rainfall observation (Z-R) also results in only suitable equation in a specific place, time and precipitation characteristics...
The rainfall estimates sometimes are underestimated, especially at small distances, but have a high correlation [16]. Moreover, the correlation between rainfall observed and radar estimates decrease when increasing the distance from the radar [10]. Furthermore, the correlation coefficient varies with the range over measured variables [17]. Ideally, the QPE radar has a same time resolution of the rain gauge data. But, this condition can’t fulfilled in the Indonesia region, which generally only have daily accumulated rainfall data. Weather radar, including new equipment installed in Indonesia by BMKG. There were 34 weather radar in this region and the radar usage is limited for the safety of aircraft and an extreme weather warning. QPE radar of this region is still rarely done because the limitations of data which has a resolution of 10 minutes, according to temporal radar. Whereas, the accumulation of rainfall in daily also can produce good QPE [18].

Difficulties of rainfall estimates in the tropical region including in Indonesia since rainfall in this region is very random. The rainfall can be varied in a short time and place. Consequently, the correlation rainfall remotes sensing estimate varies at each place [19]. This complexity is caused by the combination of local factors such as sea or mountain breeze and global driven influence rainfall in a location [20-27].

Generally, the equation of radar’s QPE relates radar’s reflectivity and rain gauge rainfall Z–R. It requires surface rainfall data which same time resolution as radar data. Therefore radar’s QPE in the day must be modified. The next problem is in choosing of the altitude of radar’s reflectivity, also determines the accuracy of radar’s QPE. Some evaluations use constant altitude plan position indicator (CAPPI) 1.5 km [28, 29], although other altitude gave better results in Thailand [15]. But low CAPPI makes low of radar coverage and must be interpolated to generate data volumes to 2D [30]. Because CAPPI ignores differences of reflectivity’s elevation, grid reflectivity is very influenced to evaluate. In this work, we identify an approach radar QPE to the assessment of daily rainfall estimates in South Sulawesi, the part of Indonesian tropical maritime using some accumulation of reflectivity data on several radius grids. Extended the range of the radar, in this work uses the PPI on the first scan of the radar.

2. Data and Method

2.1. Study Area and Data

The South Sulawesi is in the middle part of the Indonesian maritime continent (IMC) which has mountainous complex topography (Figure 1). Besides Asian and Australian Monsoon as the most influential to rainfall event in this region, other global and local-driven also influence to rainfall [20-23, 26-27, 31-32]. That makes one place may have different early in the rainfall season than other [25].

Rainfall data in Indonesian are measured and collected by the Indonesian Agency for Meteorology Climatology and Geophysics (BMKG) where the location of the rain gauge locations are distributed as shown in Figure 1. There are 248 rain gauges in 2015 which measure daily rainfall, but weather radar data only provided 3 last month this year. The radar located in Maros, about 44 km far away from Makassar, the capital city of South Sulawesi. The specifications of the Maros radar station are given in Table 1.
Figure 1. A beam of radar and location of rain gauge station in surrounding South Sulawesi. The circle is a range of weather radar.

Table 1. Operating parameters of meteorological radar in Maros

| Item         | Specification          |
|--------------|------------------------|
| WMO ID       | 0.20010.0.2333         |
| Latitude     | 4° 59' 52''S          |
| Longitude    | 119° 34' 19''E        |
| Elevation    | 19 m                  |
| Frequency    | 5600 MHz              |
| Gain         | 35-42 dB              |
| PRF          | 300± 1 PPS            |
| Pulse Width  | 0.8 - 2 µSec          |
| Power        | 250 kW                |
| Cycle Time   | 10'                   |

The format of weather radar data is in the volume scan .vol and will be converted in .csv format, so in this work use adlib, one of Python's libraries. This package can change the reflectivity data in order to flexible format to compare with daily rainfall data and useful to treat lower weather data format for Hydrometeorological and Hydrological applications [33]. Every 10 minutes of radar reflectivity is equalized with daily rain gauge observed. In this work, we use accumulation original reflectivity and accumulation inverse distance weighting (IDW) interpolation result of reflectivity in some extent of the radar grid with rainfall observed. In this research also will be examined the effect grid changes to the rainfall radar estimates. So some extent grids are used in this work. There are 0.0175°, 0.0250°, 0.0500°, 0.0750°, 0.1000°, 0.1250°, 0.2500° and 0.5000°.
Choosing altitude level determines the accuracy of the radar rainfall estimates. Some researchers use a constant altitude plan position indicator (CAPPI) 1.5 km [28][29], although other altitude gave a better result such as in Thailand [15]. The lower CAPPI make restricted in a range of coverage. For example, if chosen CAPPI 1.5 km only can reach 100 km in coverage. So, in this work use first plan position indicator (PPI) to reach all stations in Figure (1). The first swept in this work is also chosen because the first swept has a far distance of coverage to the surface location where rain gauge is located, although the further the location, higher the bias.

2.2. Quantitative Precipitation Estimated (QPE) Method

Weather radar receives reflectivity in dBZ that stands for decibel relative to Z. The dBZ is a logarithmic dimensionless technical unit and used in mostly in weather radar. It is equivalent to reflectivity factor (Z) of a radar signal reflected off a remote object (in mm$^6$ per m$^3$) to the return of a droplet of rain with a diameter of 1 mm (1 mm$^6$ per m$^3$)[34] with the formulation

$$\text{dBZ} = 10\log(Z) \quad \text{or} \quad Z = 10^{\left(\frac{\text{dBZ}}{10}\right)}$$ (1)

Then quantitative Precipitation Estimated (QPE) radar use relation of reflectivity (Z) and rainfall observed (R) with the formulation

$$Z = AR^b$$ (2)

where A and b are empirical coefficients.

Relation Z-R in equation (2) can use in all type types of rainfall (convective, stratiform or mixed types) [13]. But in daily estimates, using equation (2) has two problems. First, chosen representative of reflectivity. Maros radar has 250 m spatial resolution and if choosing a pixel of radar can be difficult because we can’t know what a pixel is representative to each place. Rainfall in a tropical region, especially in Indonesia maritime continent can have a poor correlation with remote sensing rainfall estimates in short time [19]. Determined a location pixel of radar precisely is difficult. Because we don’t know where a pixel that makes rainfall in gauge sites recorded. So in this study, we use some extended grids in QPE detection. Inverse distance weighting (IDW) interpolation is added to make...
sure that choosing grid is suitable. Second, rainfall observed only provide in daily, then we rather use original dBZ than Z in equation (1). There are 144 data in the accumulation of 10' radar data in daily.

If conversion in equation (1) is used, it can make the value of Z irrational because very big. Also, using some kinds of extent grids means that all value of dBZ in a grid is added and it can make the value of dBZ bigger. So relation dBZ and rainfall in daily use a simple linear model

$$R = a + b \times dBZ$$

(3)

The choosing suitable daily rainfall radar estimates are made in some extend the grid. The original reflectivity is accumulated in 0.01750, 0.02500, 0.05000, 0.07500, 0.10000, 0.12500, 0.25000 and 0.50000. In this work, IDW interpolation uses 0.07500 then the interpolation result is accumulated in 0.07500, 0.10000, 0.12500, 0.25000 and 0.50000 to the evaluation of the accuracy. Bright band (BB) correction and clutter are neglected in this work because no data in 10' compared to remove the erroneous.

2.3. Evaluation Method
Root mean square error (RMSE) in equation (4) is used to evaluate radar’s QPE. This investigates how much deviation between two quantitative variables, such as rainfall observed and radar’s QPE. The higher deviation can be detected with how big of RMSE.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(R_o - R_r)^2}{n}}$$

(4)

where $R_r$, $R_o$ and $n$ refers to radar’s QPE, rainfall observed respectively and a number of locations. The spatial RMSE will be shown in a spatial bubble plot and will be added the scatter plots the correlation of distance and the histogram. The Pearson coefficient correlation ($r$) is used to know the relation between weather radar reflectivity and rain gauge observed. The $r$ is formulated by

$$r = \sqrt{\frac{\sum_{i=1}^{n}(dBZ_i - \bar{dBZ})(R_i - \bar{R})}{\sqrt{\sum_{i=1}^{n}(dBZ_i - \bar{dBZ})^2 \sum_{i=1}^{n}(R_i - \bar{R})^2}}}$$

(5)

where $dBZ$, $R$, $n$ and $i$ refer to radar reflectivity, rainfall observed, a total of rain gauge station and $i$ refers to station index respectively. While $\bar{dBZ}$ refers to the average of radar reflectivity and $\bar{R}$ refers to the average of rainfall observed. The strengthen of correlation is commonly used to evaluation spatially remote sensing rainfall estimates [35][36]. We use 5 class correlation which used to analyse the elation of correlation and RMSE. There are very weak (0.0-0.2), weak (0.2-0.4), moderate (0.4-0.6), strong (0.6-0.8) and very strong (0.8-1.0).

3. Result and Discussion
3.1. Range Distance Correlation
The closest locations have higher correlation or the other hand the further sites have a lower correlation as shown in Figure 3. The highest correlation located at distance less than 50 km from the radar sites.
Radar data reflectivity in South Sulawesi closely related to rainfall observed and it may potentially produce QPE [18]. The distance of the location affects the correlation. The further away a location, the correlation between radar reflectivity and rainfall observed will decrease [10, 16-17]. Although sometimes found at close distances can also have a low correlation [28]. Moreover, the fluctuations of correlations in South Sulawesi can vary, especially at a distance of 25 km and 50 km - 80 km. There are a significant decreasing of correlation at a specific distance, where Maros radar site is worse than Moldavian radar [35], but still better than Rome radar [10].

Base on the value of correlation in daily is obtained that original reflectivity has very weak in correlation (0.0 – 0.2) respect to rainfall observed. The very weak correlation of about 81 % and 95 % of the correlation below 0.4. Using the IDW interpolation can improve relation correlation with the reduced number of very weak correlation from 81% to 74% and increased moderately from 5% to 8%. Moreover, increasing of correlation is not only in daily but also in each station rainfall time series. Different with correlation in daily reflectivity that almost stations have a low very weak correlation, in each station data very weak correlation only 50% and 15 % stations have a strong and very strong correlation. Also, IDW interpolation can increase strong and very strong correlation from 15% in original reflectivity to 22%.

### Table 2. Distribution correlation radar reflectivity and rainfall observed

| Correlation | Daily | Each Station |
|-------------|-------|--------------|
|             | IDW   | Original     | IDW   | Original |
| 0.0-0.2     | 74 %  | 81 %         | 43 %  | 50 %      |
| 0.2-0.4     | 13 %  | 13 %         | 22 %  | 22 %      |
| 0.4-0.6     | 8 %   | 5 %          | 12 %  | 12 %      |
| 0.6-0.8     | 3 %   | 1 %          | 18 %  | 13 %      |
| 0.8-1.0     | 0 %   | 0 %          | 4 %   | 2 %       |

#### 3.2. Error radar QPE

Radar rainfall estimates are obtained from the IDW interpolation reflectivity result and original reflectivity dBZ. The evaluation in daily and each station time series rainfall estimates show that the stronger of correlation has the greater the RMSE value (Tables 3 and 4) both the original reflectivity
or the interpolation result. Generally, the daily QPE is very weak or weak correlation and only a few of them have a strong correlation, especially in using original data reflectivity. The applying large grid of reflectivity will result in a relatively smaller RMSE, especially in areas of correlation of 0.0 to 0.6. Whereas in regions with correlations greater than 0.6 there is a possibility of using smaller grids of the results of IDW interpolation to produce better RMSE (Table 3).

Table 3. Average RMSE of daily rainfall prediction base on IDW interpolation use some grids, from 0.0750°, 0.1000°, 0.1250°, 0.2500° and 0.5000° in some correlation class. There are 0.0-0.2 (RMSE_0.2), 0.2-0.4 (RMSE_0.4), 0.4-0.6 (RMSE_0.6), 0.6-0.8 (RMSE_0.8) and 0.8-1.0 (RMSE_1.0).

| IDW_Grid | RMSE_0.2 | RMSE_0.4 | RMSE_0.6 | RMSE_0.8 | RMSE_1.0 |
|----------|---------|---------|---------|---------|---------|
| 0.0750°  | 7.084   | 9.908   | 24.413  | 26.873  | -       |
| 0.1000°  | 7.090   | 10.090  | 21.720  | 26.992  | -       |
| 0.1250°  | 7.051   | 9.777   | 21.056  | 26.806  | -       |
| 0.2500°  | 7.126   | 9.139   | 18.024  | 32.752  | -       |
| 0.5000°  | 6.540   | 14.347  | 16.708  | 29.878  | -       |

Table 4. Average RMSE of daily rainfall prediction base on original reflectivity use some grids, from 0.0750°, 0.1000°, 0.1250°, 0.2500° and 0.5000° in some correlation class. There are 0.0-0.2 (RMSE_0.2), 0.2-0.4 (RMSE_0.4), 0.4-0.6 (RMSE_0.6), 0.6-0.8 (RMSE_0.8) and 0.8-1.0 (RMSE_1.0).

| Radius  | RMSE_0.2 | RMSE_0.4 | RMSE_0.6 | RMSE_0.8 | RMSE_1.0 |
|---------|---------|---------|---------|---------|---------|
| 0.0175° | 7.749   | 20.981  | -       | -       | -       |
| 0.0250° | 7.488   | 21.376  | -       | -       | -       |
| 0.0500° | 7.413   | 15.896  | 42.214  | -       | -       |
| 0.0750° | 7.147   | 13.364  | 29.200  | -       | -       |
| 0.1000° | 7.120   | 13.160  | 21.863  | -       | -       |
| 0.1250° | 7.109   | 13.154  | 21.837  | -       | -       |
| 0.2500° | 7.067   | 12.246  | 19.025  | 33.890  | -       |
| 0.5000° | 6.994   | 11.039  | 21.977  | 29.964  | -       |

Based on the evaluation at each station shows that the larger grid range will result in a smaller RMSE in almost all locations (Tables 5 and 6). Also, the correlation between 0.4 to 0.8 will obtain greater RMSE compared to others. While the correlation between 0.0 to 0.2 has the smallest RMSE.

Table 5. Average RMSE of station rainfall prediction base on IDW interpolation use some grids, from 0.0750°, 0.1000°, 0.1250°, 0.2500° and 0.5000° in some correlation class. There are 0.0-0.2 (RMSE_0.2), 0.2-0.4 (RMSE_0.4), 0.4-0.6 (RMSE_0.6), 0.6-0.8 (RMSE_0.8) and 0.8-1.0 (RMSE_1.0).

| IDW_Grid | RMSE_0.2 | RMSE_0.4 | RMSE_0.6 | RMSE_0.8 | RMSE_1.0 |
|----------|---------|---------|---------|---------|---------|
| 0.0750°  | 11.303  | 12.2611 | 13.5348 | 13.963  | 11.827  |
| 0.1000°  | 10.8647 | 11.3231 | 14.4048 | 13.3513 | 11.985  |
| 0.1250°  | 10.2600 | 11.2657 | 14.3472 | 13.0677 | 11.306  |
| 0.2500°  | 8.9447  | 10.7346 | 10.8489 | 13.7773 | 12.364  |
| 0.5000°  | 9.263   | 9.8919  | 9.3094  | 13.5239 | 11.706  |
Table 6. Average RMSE of station rainfall prediction base on original reflectivity use some grids, from 0.0750°, 0.1000°, 0.1250°, 0.1250°, 0.2500° and 0.5000° in some correlation class. There are 0.0-0.2 (RMSE_0.2), 0.2-0.4 (RMSE_0.4), 0.4-0.6 (RMSE_0.6), 0.6-0.8 (RMSE_0.8) and 0.8-1.0 (RMSE_1.0).

| Radius  | RMSE_0.2 | RMSE_0.4 | RMSE_0.6 | RMSE_0.8 | RMSE_1.0 |
|---------|----------|----------|----------|----------|----------|
| 0.0175° | 9.533    | 11.412   | 13.555   | 14.672   | 12.365   |
| 0.0250° | 9.130    | 12.499   | 12.426   | 14.683   | 11.479   |
| 0.0500° | 9.013    | 11.666   | 13.647   | 14.217   | 11.539   |
| 0.0750° | 8.678    | 11.791   | 13.703   | 14.508   | 10.865   |
| 0.1000° | 8.599    | 11.588   | 13.480   | 14.784   | 10.679   |
| 0.1250° | 8.443    | 11.218   | 13.613   | 14.783   | 10.853   |
| 0.2500° | 8.316    | 10.476   | 12.515   | 14.970   | 12.844   |
| 0.5000° | 8.808    | 9.727    | 9.082    | 14.458   | 12.439   |

Figure 4 shows that the rainfall distribution represented by 1–quarter, 2–quarter (median) and 4–quarter using boxplot. They indicate that both of daily and each station rainfall evaluation has the higher in correlation, the higher rainfall fluctuation. The high deviation of daily rainfall estimates with 0.6 – 0.8 correlation in table 3 is accompanied by a wider range on the boxplot in figure 4a. Conversely, on the boxplot whose small quantile’s range between 0.0 and 0.2 correlation have the smallest of RMSE. Similarly, in the evaluation of rainfall time series of each station showed the largest RMSE occurred at 0.6 to 0.8 correlation along with wide fluctuations in rainfall. This shows the high or low of the rainfall value is supposed to be highly influential to the magnitude of RMSE. This is due to model estimation in heavy rain, usually containing a larger error than the estimation of light rainfall.

Moreover, the large deviation between model and rainfall observed occurs in the west coast of South Sulawesi (Figure 5). Generally RMSE in this region more than 15 (yellow and green). Rain due to the Asian monsoon seems to be related to the magnitude of the deviation between the radar rainfall estimate and rain observed. In the South Indonesian region, rainfall in October, November, and December where rainfall data used in this study, is linked to the western wind that contains water vapor from Asian. The three months at the end of the year is the beginning of the rainy season [25]. The rain occurred in the western coastal area higher than the rainfall on the east coast of Sulawesi. The position of a place also influences rainfall fluctuation and accuracy of remote sensing rainfall estimates [35]. In these months, the humid wind from Asia started to blow into Indonesia, but to the
east of South, Sulawesi is generally a local rain type [37]. So in this month the rainy season is still not entered in this area.

![Figure 5. RMSE distribution base on IDW radar reflectivity result (a) and original radar reflectivity (b).](image)

4. **Conclusion**

The IDW interpolation can improve correlation compared the original accumulation of radar’s reflectivity both in the daily rainfall area and each station time series. Furthermore, the interpolation could reduce the number of very weak correlation from 81% to 74% and increased moderate correlation from 5% to 8%. Conversely, the original of radar’s reflectivity resulted in very weak correlation. The evaluation in each station time series data has a very weak correlation and only 15% of correlation has a strong and very strong correlation. While using IDW interpolation can increase strong and very strong correlation from 15% in original reflectivity to 22%.

Rainfall estimates in the daily area and station time series rainfall show that the stronger of correlation has the greater the RMSE value. Also, it is not a lot of strong and very strong correlation in this region. While, rainfall estimates in each station show the use of a larger reflectivity grid will result in a smaller RMSE in almost all locations, where 0.5000° is the best grid. The higher correlation makes greater RMSE compared to others, while the area which has a correlation between 0.0 to 0.2 obtained the smallest RMSE.
The large deviation between model and rainfall observed occurs in the west coast of South Sulawesi. The Asian monsoon seems to be related to the magnitude of the deviation between the radar rainfall estimate and rain observed. The heavy or not, about rainfall appears to have an effect on radar precipitation estimates. The rainfall occurred in the western coastal area higher than the rainfall on the east coast of Sulawesi. Therefore, the position of a place also influences rainfall fluctuation and accuracy of remote sensing rainfall estimates. Where in this month of data, the humid wind from Asia started to blow into Indonesia, but to the east of South Sulawesi is generally a local rain type.

Acknowledgment

Data of this research was supported by the Indonesian meteorological agency (BMKG). The authors especially appreciate to the Maros Climatology Station. R and python, especially wradlib an open source for radar library has been used for this study.

References

[1] WMO 1994 Guide to hydrological practice: Data acquisition and processing analysis and forecasting and other applications (WMO-No168).
[2] Verworn H R 2002 Advances in urban–drainage management and flood protection Philos Trans Roy Soc Lond Ser A Math Phys Eng Sci 360(1796): 1451–1460.
[3] Einfalt T Arnbjerg-Nielsen K Golz C Jensen NE Quirmbach M Vaes G and Vieux B 2004 Towards a roadmap for use of radar rainfall data in urban drainage J Hydrol 299 : 186 202.
[4] Berne A Delrieu G Creutin J D and Obled C 2004 Temporal and spatial resolution of rainfall measurements required for urban hydrology J Hydrol 299 : 166–179.
[5] Matrosov S Y Ralph F M Neiman P J and White A B 2014 Quantitative assessment of operational radar rainfall estimates over California's Northern Sonoma County using HMT West data Journal of Hydrometeorology 15 : 393–410.
[6] Montopoli M Roberto N Adirosi E Gorgucci E and Baldini L 2017 Investigation of Weather Radar Quantitative Precipitation Estimation Methodologies in Complex Orography Atmosphere 8(34) : 1–25.
[7] Brandes E A Vivekanandan J and Wilson J W 1999 A comparison of radar reflectivity estimates of rainfall from collocated radars Atmos Ocean Tech 16 : 1264–1272.
[8] Villarini G and Krajewski W F 2010 Review of the different sources of uncertainty in single polarization radar-based estimates of rainfall Surv Geophys 31 : 107–129.
[9] Moreau E Testud J and Le Bouar E 2009 Rainfall spatial variability observed by X-band weather radar and its implication for the accuracy of rainfall estimates Advances in Water Resources 32(7) : 1011–1019.
[10] Sebastianelli S Russo F Napolitano F and Baldini L 2013 On precipitation measurements collected by a weather radar and a rain gauge network Nat Hazards Earth Syst Sci 13 : 605–623.
[11] Stout G T and Mueller E A 1968 Survey of relationships between rainfall rate and radar reflectivity in measurement precipitation J App Meteo 7 : 465–474.
[12] Battan L J 1973 Radar observation of the atmosphere (The University of Chicago Press).
[13] Ramli S and Tahir W 2011 Radar Hydrology: New Z/R Relationships for Quantitative Precipitation Estimation in Klang River Basin Malaysia International Journal of Environmental Science and Development 2(3) : 1–5.
[14] Yeo J X Lee Y H and Ong J T 2015 Radar Measured Rain Attenuation with Proposed Z - R Relationship at a Tropical Location Int J Electron Commun AEÜ 69 : 458–461.
[15] Kirtsaeng S and Chantraket P 2016 Investigation of Z-R Relationships for Monsoon Seasons over Southern Thailand Applied Mechanics and Materials 855 : 159–164.
[16] Mandapaka P V Krajewski W F Ciach G J Villarini G and Smith J A 2009 Estimation of radar-rainfall error spatial correlation Advances in Water Resources 327 : 1020-1030.
[17] Habib E and Krajewski W 2001 Estimation of Rainfall Interstation Correlation Journal of Hidrometeorology 2 : 621–629.
[18] Rossa A M Cenzon G and Monai M 2010 Quantitative comparison of radar QPE to rain gauges for the 26 September 2007 Venice Mestre flood Nat Hazards Earth Syst Sci 10: 371–377.

[19] Giarno Hadi M P Suprayogi S and Murti S H 2018 Distribution of Accuracy of TRMM Daily Rainfall in Makassar Strait Forum Geografi 32(1): 38–52.

[20] Qian J H 2007 Why precipitation is mostly concentrated over islands in the maritime continent Journal of The Atmospherics Sciences 65: 1428–1441.

[21] D'Arrigo R and Wilson R 2008 Short Communication: El Niño and Indian Ocean influences on Indonesian drought: implications for forecasting rainfall and crop productivity International Journal of Climatology 28: 611–616.

[22] Hidayat R and Kizu S 2010 Influence of the Madden–Julian Oscillation on Indonesian rainfall variability in austral summer International Journal of Climatology vol30 pp 1816–1825.

[23] Renggono F 2011 Polasebaran hujan di DAS Larona Jurnal Sains & Teknologi Modifikasi Cuaca 12: 17–24.

[24] As-sayakur A R 2010 Polas spasial pengaruh kejadian la niná terhadap curah hujan di Indonesia tahun 1998/1999: Observasi mengggunakan data TRMM multisatellite precipitation analysis TMPA 3B43 Prosiding Pertemuan Ilmiah MAPIN XVII Bandung.

[25] Giarno Zadrach L D and Mustofa M A 2012 Kajian awal musim hujan and awal musim kemarau di Indonesia Jurnal Meteorologi and Geofisika 1: 1–8.

[26] Hashiguchi H Tabata Y Yamamoto M K Marzuki Mori S Yamanaka M D Syamsudin F and Manik T 2013 Observational Study on Diurnal Precipitation Cycle over Indonesian Maritime Continent Journal of Disaster Research 8: 1–9.

[27] Lee H S 2015 General Rainfall Patterns in Indonesia and the Potential Impacts of Local Seas on Rainfall Intensity Water 7: 1750–1768.

[28] Yoon S S Phuong A T and Bae D H 2012 Quantitative Comparison of the Spatial Distribution of Radar and Gauge Rainfall Data Journal of Hydrometeorology 13: 1939–1953.

[29] Yoo C Yoon J Kima J and Ro Y 2016 Evaluation of the gap filler radar as an implementation of the 15km CAPPI data in Korea Meteorol Appl 23: 76–88.

[30] Mittermaier M P and Terblanche D E 1997 Converting weather radar data into Cartesian space: a new approach using DISPLACE averaging Water 23: 46–50.

[31] Martono M and Wardoyo T 2017 Impacts of El Niño 2015 and the Indian Ocean Dipole 2016 on Rainfall in the Pameungpeuk and Cilacap Regions Forum Geografi 312: 184–195.

[32] Supari Tangang F Salimun E Aldrian E Sopheluwakan A and Juneng L 2017 ENSO modulation of seasonal rainfall and extremes in Indonesia Climate Dynamics 1–22 https://doi.org/10.1007/s00382-017-4028-8.

[33] Heistermann M Jacobi S and Pfaff T 2013 Technical Note: An open source library for processing weather radar data (wradlib) Hydrol Earth Syst Sci 17: 863–871.

[34] Doviak R J and Zrnic D S 1993 Doppler radar and weather observation (Academic Press)

[35] Burcea S Cheval S Dumitrescu A Antonescu B Bell A and Breza T 2012 Comparison between radar estimated and rain gauge measured precipitation in the Moldavian Plateau Environmental Engineering and Management Journal 114: 723–731.

[36] Prasetia R As-syakur A R and Osawa T 2013 Validation of TRMM Precipitation Radar satellite data over Indonesian region Theory Applied Climatology 112: 575–587.

[37] BMKG Maros 2015 Buletin prakiraan hujan 2015.