WRF-3DVAR Radiance Data Assimilation Impact for Convective Rain Prediction on Jakarta

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Abstract. Weather Research and Forecasting (WRF) is an open source numerical weather prediction model, but one of the main problems is the inaccuracy of initial condition that impacts the accuracy of weather predictions. Techniques that can be used to improve initial condition is to assimilate satellite radiance data using Three-Dimensional Variation (3DVAR) method. The Global Forecast System (GFS) data were used as initial conditions which were assimilated with several radiance data such as from AMSU-A sensors, MHS sensors, and ATMS sensors. The purpose of this study was to compare the effect of data assimilation on the initial condition model and the rainfall prediction for convective precipitation on February 24, 2016 in Jakarta. The results showed there is a clear flow of moisture to the northern part of Jabodetabek area that cause the model captured a high relative humidity which results in the heavy rain. The result of the study obtained different rainfall prediction between non-assimilation model and assimilation model. In general, both models have underestimated rainfall, but satellite radiance data assimilation is better able to describe the convective rain patterns and has better accuracy on the convective rainfall accumulation per hour.

Keyboard : WRF-3DVAR, radiance, assimilation, convective.

1. Introduction

Precipitation consists of two types which is stratiform and convective. Stratiform precipitation falls from stratus, stratostratus, and nimbostratus clouds, while convective occurs from cumulus and cumulonimbus clouds [1]. This type of cloud may occur separately or in the same cloud complex. Convective precipitation occurs in relation to strong low-level convergence. Convective clouds cause local rain that occurs due to convection located in unstable air [2]. Rain from the convective cloud has a large rainfall intensity, from moderate to heavy rain (shower). Rainfall from convective clouds has a value of >10 mm / hour [3]. Because of the high rainfall intensity, it often causes flooding in the Jakarta area, so it is imperative to use a high-resolution heavy rainfall forecast as an important role to produce accurate forecast for warning information for operational purposes. One of the latest generations of the meso scale model of Numerical Weather Prediction (NWP) is Weather Research and Forecasting (WRF). WRF model has good potential in observing rainfall events such as rain time, location, and evolution [4]. But the accuracy of rainfall forecasts is also influenced by many factors in the dynamic part of the numerical model, especially the uncertainty of the initial conditions [5]. Improvements to the initial conditions can improve the accuracy of rainfall forecasts [6] which can be done through data assimilation on the WRF model. Data assimilation is a method of improving the initial conditions of the atmosphere as a model input by calculating the observation data into a grid model system [7]. The
application of data assimilation in the NWP model consists of several techniques, one of which is The Three-Dimensional Variation (3DVAR). 3DVAR techniques have better performance in producing rational analysis of hydrometeorological events with greater computational efficiency than other techniques [8].

The data used for assimilation consists of various types of data, ranging from surface observation data, upper air observation data, remote sensing data, and the combination of these types of data. The lack of surface-based weather observation platforms creates problems in monitoring meso-scale weather systems and rainfall characteristics in an area. Although there have been already many papers about this topic, but only several of them that discuss the effect of satellite radiance data assimilation in the tropic region, especially in Jakarta area. Therefore, it is necessary to use satellite observation data which has a wider scope of observation to cover the shortcomings of the surface weather observation platform. Moreover, because the satellite data used in assimilation is polar orbit satellite to some extent, not all satellite data can be used in an event in an area. Even though the initial global model data has been assimilated by satellite radiation data, but when downscaling is finished, it is uncertain that the area and time of the event taken as a case have been assimilated or not. Consequently, it is very necessary to further assimilate each domain that has been downscaled to ensure that each domain has been influenced by the assimilation of satellite radiation data. Based on data from rsl.out.0000 of the assimilation results, it shows the satellite radiance data has successfully assimilated hundreds of data from satellites that crossed the WRF model’s first guess data. Based on the previous research that investigate Quantitative Precipitation Forecast (QPF) skill evaluating the influence of data assimilation for rainfall prediction in Java region show that radiance data assimilation has slightly contribution on rainfall prediction, but it presented better accuracy on rainfall prediction for the heavy rainfall cases [9]. Moreover, the other results from WRF data assimilation that examine rainfall prediction in Jakarta region using satellite data assimilation provides the best effect compared to other assimilation models, but it still overestimates compared to the observational data [10]. The addition of satellite radiance assimilation data has an impact on improving the quality of forecasts, initial conditions, spatial patterns of rainfall and rainfall intensity [5, 11].

This proves that satellite data can have a positive impact on forecast results through the method of data assimilation in the WRF model. Direct radiance assimilation is theoretically superior to retrieval assimilation because the observational error statistics are more justified in direct radiance assimilation than in retrieval assimilation [12]. This approach requires an observation operator built into the data assimilation system to transform model variables into radiances. The linkage between forecast model state variables and observed radiances is expressed mathematically by a Community Radiative Transfer Model (CRTM) that was developed by the U.S. Joint Centre for Satellite Data Assimilation (JCSDA) to provide fast, accurate satellite radiance simulations, which calculates radiance from model state vertical profiles. In this study, the WRF-3DVAR system is used to explore the effect of the assimilation of NCAR AMSU-A and MHS microwave radiance data on forecasts of heavy precipitation on the Jakarta region. This study aims to see how far the results of predictions of numerical rainfall predictions have improved after assimilation of satellite radiance data when compared to models without data assimilation. This paper is organized as follows, Section 2 gives a concise overview of the method and experiment design. Section 3 provides information on the study area and the data. The results of the data assimilation experiments are presented and evaluated in Section 4, and conclusions are given in Section 5.

2. Method and experimental design

2.1. WRF model set up

The numerical data assimilation experiments in this study are conducted using the Advanced Research WRF model Version 3.8. WRF is a model of numerical weather prediction systems and atmospheric simulations designed for both research and operations [7]. WRF-ARW has been developed in recent years and is designed to be a sophisticated and efficient atmospheric simulation system on existing parallel computing platforms [13]. As shown in Figure 1, we use two nested model domains with 9 km
(100 × 100) and 3 km (75 × 75) horizontal spacing. Each domain has 28 vertical pressure levels with the top-level set at 50 hPa. The WRF physical parameterization schemes used in this study include the Purdue Lin microphysical parameterization, Rapid Radiative Transfer Model (RRTM) longwave radiation, Dudhia shortwave radiation, Monin Obukhov surface layer, Noah land surface, Yonsei University (YSU) planetary boundary layer scheme, and Kain Fritsch (KF) cumulus scheme. The projection method is Mercator.

**Figure 1.** Domains for the WRF ARW. The outer box is the coarse grid with a resolution of 9 km (d01); the inner box is the nested grid (d02) with a resolution of 3 km.

### 2.2. Satellite radiance data

Satellite data is very important in the forecast process using the NWP model because assimilation of sounding satellite data can significantly improve temperature and humidity forecasts [14]. Data on Global Data Assimilation System (GDAS) Satellite Radiance Data (ds735.0) in PREBUFR format as data used in the process of assimilating radiance satellite data into WRFDA provided by NCEP. In this research, the Advanced Microwave Sounding Unit (AMSU-A) and Microwave Humidity Sounder (MHS) satellite sensors are found on NOAA-15 and NOAA-18 satellites. AMSU-A has spatial resolution at nadir points of 48 km and measures in 15 spectral bands and divided into two separate units: AMSU-A1 dan AMSU-A2 [15]. AMSU-A2 with two channels at 23.8 GHz and 31.4 GHz and AMSU-A1 with twelve channels in the range 50.3 GHz up to 57.290344 GHz plus one channel at 89.0 GHz. The 12 oxygen-band channels (channels 3–14) will provide microwave temperature sounding for regions from the Earth’s near surface up to about 42 kilometres or from 1000 millibars to 2 millibars. The extreme spectral windows (channels 1, 2 and 15) allow correction of the other measurements for surface emissivity, atmospheric liquid water and total precipitable water. These channels also provide information concerning precipitation, sea ice and snow coverage. While MHS has spatial resolution at nadir of 16 km and has five-channel microwave radiometer, which complements the Advanced Microwave Sounding Unit-A (AMSU-A) channels [15]. Humidity profiles are planned to be derived from data in this frequency range. Information about cloud liquid water content, precipitation, and precipitation rates is also derived from these channels.
2.3. Data assimilation system
Data assimilation can be defined as a technique where observation is combined with NWP products and error statistics to provide a means to combine all available information to make the best estimates of atmospheric conditions [16]. The basic purpose of the variational data assimilation system is to produce optimal forecasts of the actual atmospheric state at the time of analysis through the iterative solution of the cost function equation. The following is the cost function formula for the 3DVAR assimilation method [17]:

\[ J(x) = J_o(x) + J_b(x) = \frac{1}{2}(y^0 - H(x))^T R^{-1}(y^0 - H(x)) + \frac{1}{2}(x - x^b)^T B^{-1}(x - x^b) \]  

where \( J_b \) and \( J_o \) represent background and observational terms respectively, \( H(x) \) is an operator used to transform the model grid points analysis \( x \) to observational space, and \( B \) and \( R \) are the background and observation error covariance matrices respectively. The minimization procedure changes \( x \) iteratively in order to approach the (unique) minimum of \( J(x) \) and as a result, the analysis \( x^a \). There are three input data for the data assimilation process, namely first guess data \( x^b \), observation data \( y^0 \), and background error (B) data [13].

2.4. Experimental Design
Two sets of experiments have been conducted using two domains and run for two days from February 24 to February 25, 2016 in Jakarta region. The model simulation without data assimilation will be referred to as the control experiment (CTRL). While assimilation experiments are designed using satellite radiance data in the SATA experiment which assimilated AMSU-A and MHS radiance data.

3. Study area and data
As shown in figure 2, the study area of Jabodetabek (Jakarta Bogor Depok Tangerang and Bekasi) which is on the north coast of Java Island. A total of 2 national observation stations have been used to verify the temporal distribution of the simulated precipitation every hour, they are Soekarno-Hatta station and Kemayoran station.

![Figure 2. Location map showing study area and 3 observation stations](image)

The initial and boundary conditions necessary to run the WRF are the GFS (Global Forecasting System) data at 0.25° x 0.25° grid resolution obtained from the National Centre for environmental Prediction (NCEP). This is because we want to simulate the precipitation forecast in the region of Jabodetabek. In the model integration, the coordinates of the central point are 6.117°S and 106.65°E. The WRF-3DVar experiment was conducted with the aim of modifying the initial condition data model obtained by assimilating other observation data. The assimilated data includes NCAR satellite radiance
data from AMSU-A and MHS radiance data. The data are initially downloaded in PREPBUFR format and can be assimilated directly into WRFDA. The AMSU-A and MHS satellite radiance data (NOAA-15/18) from the NOAA ATOVS instruments can be read in WRFDA via CRTM2.0.2, which is in BUFR format.

4. Results and discussion

4.1. Impact of data assimilation on the initial fields

The purpose of data assimilation is to improve the initial condition data of the model. To find out the changes and improvements to the data of the initial condition of the model, an analysis of the initial conditions of the model will be carried out without assimilation of data and models with assimilation of satellite radiance data. The parameters used in the analysis are moisture flux, air temperature, and wind at an altitude of 850 hPa.

Figure 3. The 850-hPa moisture flux for initial condition for the (a) CTRL and (b) SATA

Figure 3 shows the moisture flux between control experiments and data assimilation. Compared with CTRL experiment (Figure 3(a)), there is only a slight change of moisture flux in SATA (Figure 3(b)). The moisture flux of SATA experiment is slightly increased in the south of the study area. It may bring more precipitation in the Jabodetabek region. The moisture flux of SATA experiment also shows marked increases in the northern part of the Java Island in comparison with the control experiment.

Based on the previous experiment that also stated that the use of satellite radiance assimilation had a large influence on the parameters of air temperature and atmospheric humidity in the tropics, while another assimilation such as radiosonde was more dominant in extratropical regions [18]. The 850-hPa circulations (figure 4) from both experiment over domain 2 show that an eastward moving wind occurs in the study area. In the Jabodetabek area, it is also seen that there is a slowing in the wind speed that allows the occurrence of air mass associations around the area. Besides that, based on the air temperature (shade) in the SATA experiment (figure 4 (b)) also shows that the Jabodetabek area is also warmer when compared to the CTRL experimental model (figure 4 (a)). The warmer the air temperature in the lower layers of the atmosphere can potentially affect the air flow where air flows into places with higher temperatures. This is in accordance with the existence of an air mass slowdown as indicated by the wind vector. However, there is a convergence zone located in Jakarta region at 1400 UTC 24 February in DA experiment.
The 850-hPa humidity and circulations at 1200 UTC, 1800 UTC 24 February and 0000 UTC 25 February over domain 2 for CTRL and SATA are shown in figure 5. The initial relative humidity at 1200 UTC in the CTRL is at least 20% higher than that of SATA in the southern of Jabodetabek. The temperature is about 0.4 °C lower than that of SATA in the Jabodetabek. The temperature at 1200 UTC in SATA improved in the southeast of Jabodetabek compared with the CTRL. At 1800 UTC, a clear convergent flow and weak north-westerly wind flow occurred over the Jabodetabek area in both models, and the relative humidity of above 90% controlled the whole Jakarta area for SATA experiment (figure 5(e)). While in CTRL experiment, it only shows around 80% - 85% of relative humidity in the Jakarta area and above 95% over Bekasi. The wind flow in the SATA forming a convergence in the southern of Jabodetabek at 1800 UTC 24 February and 0000 UTC 25 February stronger than in CTRL experiment. Meanwhile, at 0000 UTC 25 February, the relative humidity of above 95% is mainly located over Jabodetabek area in model simulations. Differences of temperature and humidity from initial conditions lead to a displacement of the moisture flux in the CTRL and SATA. As the convergences move and enhance in the southern Jabodetabek, the relative humidity of SATA experiment seems to be increased at 1800 UTC 24 February and 0000 UTC 25 February over Jabodetabek. To summarize, the WRF model presented the favourable mesoscale synoptic conditions for convective precipitation over Jabodetabek. Inaccurate initial fields are particularly associated with the location errors and underestimated precipitation. Assimilation of the satellite radiance data has a positive impact on the initial fields, but the convergence still cannot be placed in the right position.

4.2. Impact of data assimilation on the precipitation forecast

From Figure 6 almost both simulations underestimated rainfall accumulation at all two observation points. Underestimation can be seen in the diagram where both all model simulations have a lower accumulation value of rainfall compared to the data of rainfall accumulation of observation stations. Although the intensity and accumulation of rainfall from some outputs of the model still underestimate when compared with rainfall observation data, but the SATA assimilation model can describe rain patterns similar to the data from observation points. The SATA experimental model has a rain pattern that is similar to the rain-gauge data at both observation points although it still shows an underestimate value for rainfall. While the CTRL experiment still cannot capture the rain pattern and is less accurate in simulating convective rain peaks. This can be caused by the influence of satellite radiance data assimilation in improving the initial conditions data on air temperature parameters and atmospheric humidity [5].
Figure 5. The 850-hPa relative humidity (shade; %) and wind (vector; m s\(^{-1}\)) over domain 2 for CTRL and SATA. (a-b) 1200 UTC 24 February, (c-d) 1800 UTC 24 February, (d-e) 0000 UTC 25 February.
The possibility of the number of rains forecast estimates according to predictions but not occurring is presented through POFD values, while the POD index is an index to show the probability of events that can be detected by the model (hit rate). Based on Table 1, the POD value of the model that has been assimilated by satellite radiance data is higher than the model that has not been assimilated, this shows that the level of truth from the prediction of rain events generated by the radiance data assimilation model is better than the model without assimilation. In addition, the model performance after data assimilation is also shown by the lower POFD value compared to the model without assimilation. This lower POFD value indicates that the model prediction error rate when there is no rain is also better when compared to the model before assimilation. So that based on the results of point verification, the satellite radiance data assimilation model has a better performance in predicting rain events compared to models without assimilation.

### Table 1. POD and POFD of control and assimilation experiment

|       | CTRL | SATA |
|-------|------|------|
| POD   | 0.66 | 0.76 |
| POFD  | 0.50 | 0.44 |

The results of WRF rain prediction both WRF without assimilation and WRF output assimilation of satellite radiance data were also verified against GSMaP rain estimation data. Regridding process needs to be carried out first between WRF data and GSMaP data which aims to equalize the second grid data resolution. The results of daily rainfall accumulation in the GSMaP data show that the rainfall area is on the north coast of Java and Banten, while for the Jakarta area there is light rain with an intensity of 20 mm - 50 mm. Meanwhile, the WRF model of both assimilation and without assimilation also shows that the area of rain tends to be more widespread in the Java Sea which causes the model to overestimate the region. In addition, the model is still not able to capture the occurrence of heavy rain that occurred in the Banten region. Rain intensity shown by both models in the area of heavy rain is still very far from the actual intensity, this causes the model to underestimate to predict the occurrence of heavy rain to very heavy.
Hence, even though the two experimental models are less able to capture the occurrence of rain, the model without assimilation has more overestimated precipitation area compared to the assimilation model. As for the assimilation model, even though it is overestimated, the value is still smaller. The results of the analysis of the WRF prediction model show that the WRF prediction model with assimilation of satellite radiance data gives a better influence compared to the model without assimilation. This is due to an improvement using satellite radiance data which adds the radiation temperature of the cloud peak temperature in the calculation of the initial conditions of the WRF model [19]. As previously shown, there is a change in the value of the initial condition of the model after assimilating satellite radiance data even though the changes are small. These small changes are caused by ignoring small-scale features or local characteristics of a region when using 3DVAR assimilation techniques which produce a homogeneous contour [20] and also the number of satellite radiance data that assimilated is very low / limited because it uses polar orbit satellite. Using direct assimilation of satellite radiance data gives positive results on the initial condition data and a significant increase in the simulation of heavy rain events up to 24 hours [5]. Even though infrared and microwave radiances have been assimilated successfully in the original operational GFS forecast system since 1998 using a clear-sky approach [21] and the all-sky AMSU-A radiance assimilation and became operational in the 4D EnVar GFS system upgrade of 12 May 2016 [22], but GFS model is run using the previous model so data assimilation is very important to combine irregular observations to generate the initial conditions that are distributed on regular model grids [23], therefore it is neccesary to assimilate the instruments in downscaling process to update the initial condition data.

5. Conclusions
In this study, the 3DVAR assimilation system is used to improve the forecasting of heavy rainfall in Jabodetabek area. A control and satellite radiance data assimilation experiments were designed. These experiments demonstrate that the improvement of the rainfall prediction by the assimilation model is still not too significant, but in general, satellite radiance assimilation can reduce the distribution of the overestimated area and intensity of the precipitation, through enhancing the accuracy of the initial field. For the point verification, rain-gauge data from 2 sites were used to evaluate the impact after data assimilation, and resulted that data assimilation experiment has the same pattern as the measured rainfall intensity by the rain-gauge instrument. The result shows that SATA experiment has higher accuracy and lower error rate in predicting rain events compared the model without assimilation. And also, the cumulative curve in both experiments is below the curve of the observed rainfall, but SATA experiment has the closest value to the observed rainfall. In conclusion, based on the results of verification, the satellite radiance data assimilation experiment has a better performance in predicting rain events compared to models without assimilation. These results indicate that efforts are still needed to improve the model prediction results in the case of rain events. Utilizing more satellite radiometer data into the

Figure 7. Simulated daily precipitation (mm) over the study area for the CTRL (b) and SATA (c), together with the observed (GSMaP) daily precipitation (a) during 24 February 2016
model as the initial conditions could specifically benefit the heavy rainfall nowcasting. In addition to improving the initial condition data model, improvements to static data on WRF models such as topography and land cover are also needed to improve the accuracy of rainfall predictions.

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