Sensitivity Test of Betts-Miller-Janjic and Grell-3D Cumulus Schemes on WRF-ARW Model to Simulate the Heavy Rainfall Event in Lampung (Case Study: 20 February 2017)

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Abstract-Lampung is a southernmost province on the island of Sumatra, Indonesia. The occurrence of heavy rain on 20 February 2017 caused flooding in some areas in Lampung. The heavy rain that lasts long enough, from 11:40 UTC to 23:00 UTC, is due to a group of convective clouds that form the Mesoscale Convective Complex (MCC) which observed on Himawari-8 satellite images. Data used in this research are FNL (Final Analysis) data from http://rda.ucar.edu/, Himawari-8 data from BMKG, and GSMaP rainfall data from ftp://hokusai.eorc.jaxa.jp. The aim of this study is to test the sensitivity of two cumulus parameterization schemes of WRF, they are Betts-Miller-Janjic and Grell-3D. Testing is done by using spatial verification and statistical verification. Overall, the output of both schemes shows that the Grell-3D scheme is good enough to describe the occurrence of the heavy rain event. Based on the results of the analysis of both schemes, it is shown that the atmospheric conditions over Lampung are very wet which is indicated by the height of the air moistness in each layer and supported by the convergence area and also the height of CAPE value which supported the formation of convective clouds during this heavy rain event.

Keywords: *cumulus schemes, WRF-ARW, heavy rain*

1. Introduction

Indonesian is an area with complex weather and climate characteristics. Indonesia is an area with complex weather and climate characteristics. In terms of its geographical location, Indonesia is a tropical region that receives a lot of solar thermal radiation so that evaporation activity in this region is very high. So as one of the countries in the tropics, extreme weather such as heavy rain is very potential to occur in Indonesia. The process of cloud growth has an important role in all types of rainfall. To know the processes in the growth of the cloud is required a simulation method that is able to describe the actual condition of the atmosphere.

On 20 February 2017, there was a heavy rain that lasted for a long time in the area of Lampung. Due to heavy rains that occurred with a long duration and covering a large area resulting in floods that occurred in several areas in Lampung. This heavy rain occurred due to the convective cloud growth above the area of southeast Lampung starting at 11:40 UTC. It turns out that a collection of convective clouds that clump over the area of Lampung is a Mesoscale Convective Complex (MCC) when viewed from Himawari-8 satellite data through Satellite Animation and Interactive Diagnosis (SATAID). The magnitude of the impact caused this incident interesting to study using the weather model.

Weather Research Forecasting (WRF) is a mesoscale weather model created for the purposes of analysis and forecasts of atmospheric conditions. WRF can model atmospheric conditions in a region so as to assist in better studying a meteorological event (Hadi et al., 2011). In carrying out WRF necessary assumptions to effect that can't be taken into account by the model called parameterization. There are various parameters in the WRF model, such as cloud microphysics, cumulus convection, hot-surface flux, momentum, moisture, and vertical mixing in the planetary boundary layer (PBL). In order to assess and predict the convective situation, it is necessary to use the schemes in conjunction with cumulus parameterization to avoid over-estimate rainfall on the grid scale, due to unrealistic feedback between heating in the lower layers, decreasing surface tension, layer convergence down and upward movement (Dinesh et al., 2016).

According to Kurniawan (2014), the Betts-Millet-Janjic cumulus parameterization scheme is made to represent the quasi-equilibrium conditions (convective clouds that maintain the temperature and humidity structures in the atmosphere) that occur when convective is strong and useful to avoid the uncertainty arising from the determination of parameters not directly using complex cloud model equations. While the Grell-3D cumulus parameterization scheme is a development of the Grell scheme developed in 1993 which performs calculations on each grid and then the results are be averaged to get feedback to the model.

The purpose of this research is to know the most appropriate cumulus parameterization scheme in describing the incidence of heavy rain in Lampung region and the effect of using different grid resolution. In addition, analysis of atmospheric conditions at the time of the event is also important to do to determine the state of the atmosphere before, during, and after the incident.

2. Data and Methods

2.1. Data

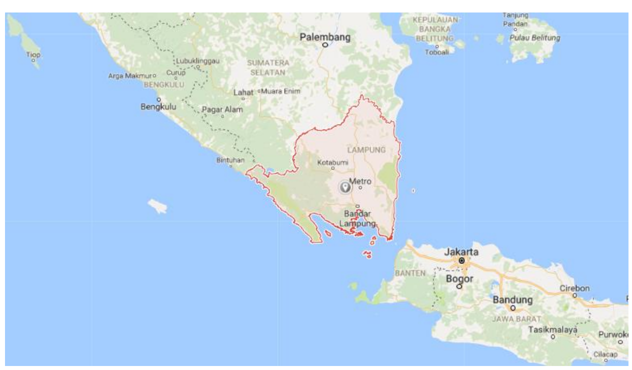

Fig. 1. Map of the province of Lampung (Google Maps Views)
[Source: Web-1]

The study was conducted in Lampung and its surroundings with coordinates of 102°-109°E and 2°-8°S. The Lampung region is the southernmost part of the island of Sumatra which borders on the waters thus allowing strong convective activity in this region. The data used in this research are FNL (Final Analysis) data on 20 and 21 February 2017 with 6-hours temporal resolution and has 1°x1° spatial resolution which downloaded through https://rda.ucar.edu.site, GSMaP (Global Satellite Mapping of Precipitation) JAXA rainfall data with 1-hour temporal resolution and 0.1°x0.1° spatial resolution downloaded from ftp://hokusai.eorc.jaxa.jp, and infrared channel (10.4μm) of Himawari-8 infrared (10.4 satellite image data from BMKG which used to detect the occurrence of heavy rain caused by the Mesoscale Convective Complex (MCC) phenomenon.

2.2. Model Configuration

Weather Research and Forecasting (WRF) is one of the numerical mesoscale weather models in the form of weather forecast and analyses developed by the National Centre for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA). WRF is a compressible and non-hydrostatic mesoscale model (Yang et al., 2014). The WRF model used in this study is WRF-Advanced Research WRF (WRF-ARW) model version 3.8.1 which used two domains with one-way nesting (Figure 1). The horizontal grid configuration used in this study is 100x100 and 75x75, with horizontal 18 and 6 grids spacing for both running process in WRF-ARW. The outermost domain covers most of Sumatra, Kalimantan, and Java, while the deepest domain (2nd domain) is centred on Lampung region. The time step configuration for both domains is 5m and 2m respectively. And the physical options used in this study are summarized in Table 1 below.

Table. 1. WRF-ARW model configuration used in this study

WRF-ARW Model Configuration	**1st Domain**	**2nd Domain**
Grid-Point Distance	18km	6km
Graphics Data Resolution	5m	2m
Microphysics Option	Lin et al scheme	Lin et al scheme
Cumulus Parameterization Option	*BMJ and Grell-3D (compared)*	
Shortwave Radiation Option	Dudhia scheme	Dudhia scheme
Longwave Radiation Option	RRTM scheme	RRTM scheme
Boundary-Layer Option	YSU scheme	YSU scheme

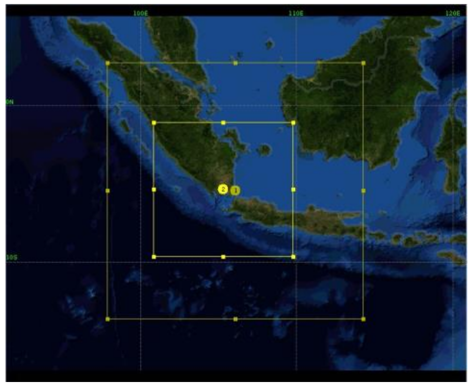

Fig. 2. Domain of research area in WRF-ARW model

2.3. Research Settings

In this study, two different configurations of WRF-ARW model are performed. For the first run, the physical option and domain configuration are performed according to Table 1 which in the cumulus parameterization option use the Betts-Miller-Janjic (BMJ) scheme. For the second run, the cumulus option is changed to Grell-3D scheme with the same fixed domain configuration as the first running. The use of different cumulus parameterization is intended to test which scheme can illustrate the occurrence of heavy rain on 20 February 2017 in Lampung region well. When using BMJ scheme, the advantages of this scheme are good for use in humid environments, doesn't require much calculation, the most efficient scheme to keep the microphysical scheme from making convective clouds, and treat elevated convection better than other schemes (Kurniawan, 2014). While according to the equations used in the Grell-3D scheme has the most fundamental difference that the use of an ensemble approach to some physical parameters that occur in the cloud and explicit rainfall forecasting approach makes this scheme suitable for use at high resolution.

In addition to the use of different cumulus schemes, in this study will also use different grid resolutions as well as listed in Table 2. It is intended that in addition to knowing the best cumulus scheme in describing the event of heavy rain, it also can know which resolution is best used in the analysis of mesoscale events. While according to Kurniawan (2014), the equations used in the Grell-3D scheme have the most fundamental difference with the equations of the BMJ scheme, such as the use of an ensemble approach to some physical parameters that occur in the cloud and the explicit forecasting approach of rainfall that make Grell-3D scheme more suitable for use at high resolution.

In addition to the use of different cumulus schemes, in this study will also use different grid resolutions as well as listed in Table 2. It is intended that in addition to knowing the best cumulus scheme in describing the event of heavy rain, it also can know which resolution is best used to analyse the mesoscale events, especially in the region of Lampung.

Table. 2. Information of WRF-ARW running process

Experiment Name	Grid Point Distance	Parameterization Scheme		
		Cumulus Option	Boundary-Layer Option	Microphysics Option
Scheme 1	18km and 6 km	BMJ scheme	YSU scheme	Lin et al scheme
Scheme 2		Grell-3D scheme		

2.4. WRF-ARW Performance Test

After WRF produces output data, the data extension is '.ctl', by using GrADS (The Grid Analysis and Display System) be done mapping some elements of weather such as humidity, wind, vorticity, rainfall, and vertical velocity. And then the rainfall data from the model output is verified used GSMaP data either spatially or statistically. Gustari et al (2012) list several statistical methods that can be used in calculating model performance such as threat score (TS), accuracy, Probability of Detection (POD), False Alarm Ratio (FAR), and bias. Threat score (TS) shows a comparison of forecasts for "yes" events with "yes" events observed. The value ranges from 0 to 1, where the best prediction is worth 1.

$$\mathrm{TS} = \frac{Hits}{Hits + False\ Alarm + Misses} \tag{1}$$

Accuracy shows the correct overall forecast section. The value is between 0 and 1. The perfect forecast is indicated by a value of 1.

$$\mathrm{Accuracy} = \frac{Hits + Correct\ Negatives}{Total} \tag{2}$$

The Probability of Detection (POD) shows the probability of events that can be detected by the model, a part of the observed event "yes" and predicted. The value is between 0 and 1, with the best value being 1.

$$\mathrm{POD} = \frac{Hits}{Hits + Misses} \tag{3}$$

False Alarm Ratio (FAR) is an event that predicts "yes" but does not occur. The value is between 0 and 1, with the best value indicated by a value of 0.

$$\mathrm{FAR} = \frac{False\ Alarm}{Hits + False\ Alarm} \tag{4}$$

Bias is the frequency of a forecast event compared to the observed event. The value ranges from 0 to ∞, with the best value being 1.

$$\mathrm{Bias} = \frac{Hits + False\ Alarm}{Hits + Misses} \tag{5}$$

3. Result and Discussion

3.1. Satellite Imagery Analysis

The results of cloud classification on infrared (IR) or 10.4mm satellite channel images obtained from Himawari-8 satellite indicate that during the event of heavy rain on

20 February 2017 in Lampung area is covered by cloud with a very wide coverage which the cloud top temperature reaching ≤-80°C. After analysis using GMSLPD software, it is known that the cloud cluster cover Lampung area is a Mesoscale Convective Complex (MCC). It is indicated that the cause of heavy rain in Lampung area is caused by clusters of convective clouds or so-called MCCs that have a lifespan of 12 hours (11:40 – 23:40 UTC).

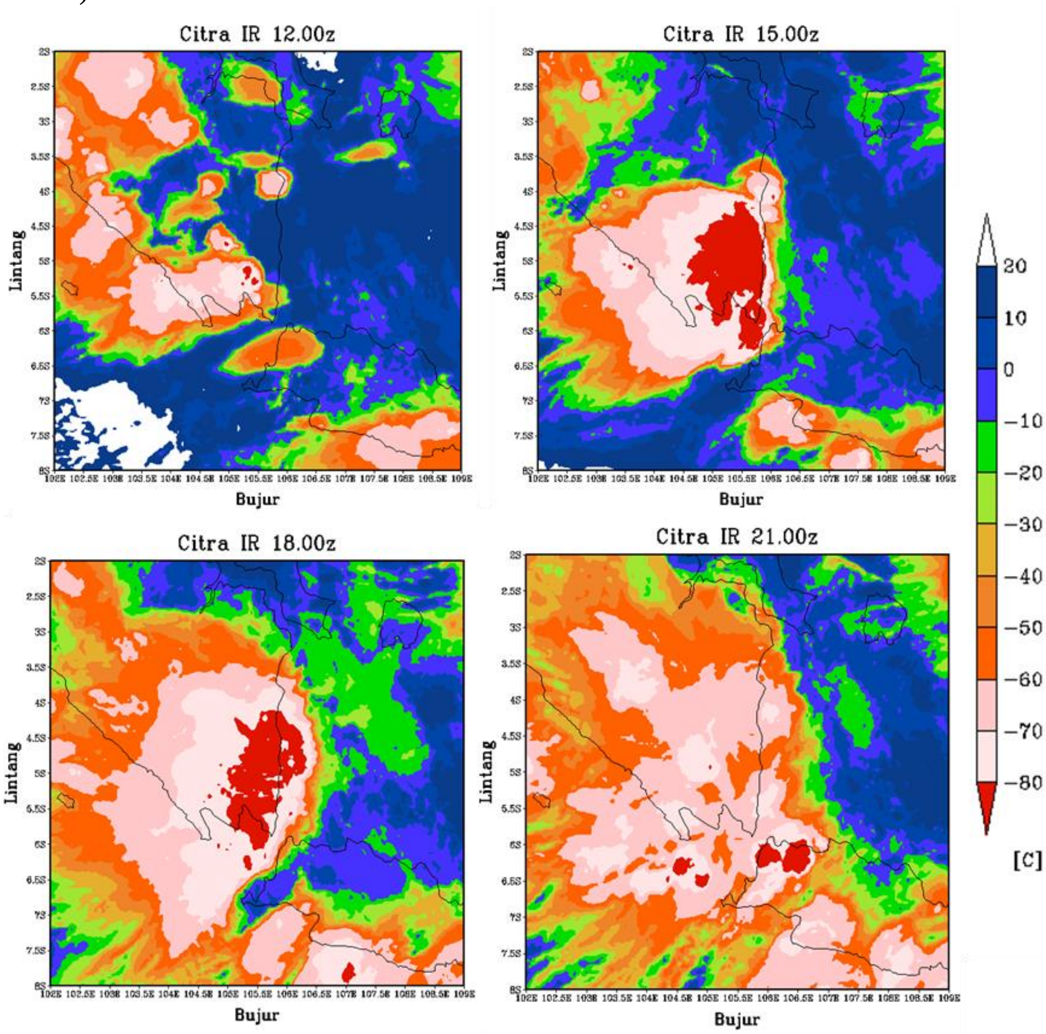

Fig. 3. IR channel of Himawari-8 satellite imagery from 12:00 UTC to 21:00 UTC

3.2. WRF-ARW Model Verification Spatially

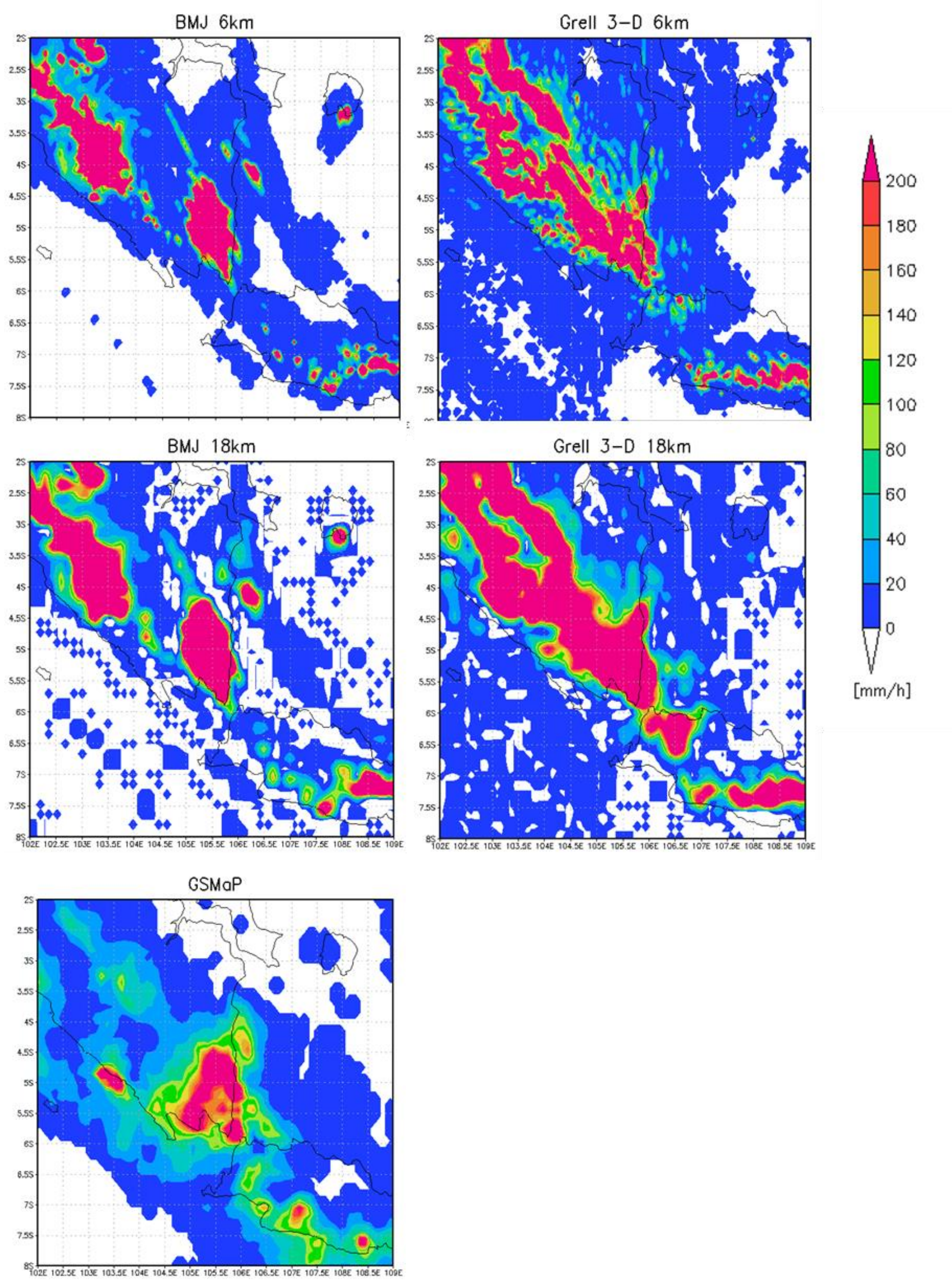

Fig. 4. Map of rainfall distribution in the research area based on GSMaP and WRF-ARW output data on 20 February 2017

Based on the map on the GSMaP rainfall distribution map shows the high rainfall intensity in the south-eastern part of Lampung with rainfall >200 mm/day based on GSMaP data. The high amount of rainfall is also seen in the other four schemes. However, from the four schematic drawings, it is seen that the pattern of rain distribution of the output of each scheme is different from the pattern of rain distribution using of GSMaP data.

From the four scattered rainfalls model output, that shown the rainfall intensity value on 20 February 2017, shows different values and has a pattern that is also different from GSMaP results. The overall scheme shows the amount of rainfall >200 mm/day in the south-eastern part of Lampung, but the coverage of the rainfall distribution area in each scheme is different. Where the Grell 3-D scheme has a very wide area of rain coverage. While the BMJ scheme has rainfall coverage almost similar to the rainfall area of GSMaP output, although there is a difference of intensity in the central part of Sumatra. Regarding the difference in resolution on each scheme is enough to give a significant effect. Can be seen from the distribution and data of rainfall intensity in each region. Where the 6 km resolution gives more detailed results and better compared with 18 km resolution.

3.3. WRF-ARW Model Verification Statistically

WRF-ARW model verification is done by comparing the model output rainfall data with GSMaP rainfall data using contingency table. In the contingency table, we will know the number of Hits, False Alarms, Misses, and Correct Negatives that will be used to calculate the Threat Score (TS), Accuracy, Probability of Detection (POD), False Alarm Ratio (FAR) and Bias of the four schemes.

Table. 3. Comparison of WRF-ARW Model Verification Results

WRF-ARW Running Scheme	TS	Accuracy	POD	FAR	Bias
BMJ 18 km	0.688	0.722	0.917	0.083	1.250
Grell-3D 18 km	0.917	0.944	0.917	0.083	0.917
BMJ 6 km	0.750	0.778	1.000	0.000	1.333
Grell-3D 6 km	0.800	0.833	1.000	0.000	1.250

Based on table 3 it is known that the highest Threat Score (TS) value of the four schemes is found in Grell-3D scheme with 18 km resolution with value 0.917. The highest accuracy value of the four model results is also found in Grell-3D scheme with 18 km resolution with value 0.944. The highest Probability of Detection (POD) is found in BMJ and Grell-3D scheme with 6 km resolution, both of which have a perfect value that is 1. Similarly, the highest value of False Alarm Ratio (FAR) is also found in BMJ and Grell-3D scheme with 6 km resolution for the lowest FAR value. As for the lowest bias value found in Grell-3D scheme whose value is almost close to 1.

3.4. Analysis of Atmosphere Condition

3.4.1. Divergency

The value of divergence describes the presence or absence of a slowing of the wind speed so as to make the air mass become collected or disintegrated. In Figure 5 explains the change in divergence values before, during, and after the event of heavy rain in Lampung region. In layers of 1000-850 hPa divergence values in the Lampung region before the occurrence ranges from $-6x10^{-6}$ s^{-1} to $<-12x10^{-6}$ s^{-1}, when dense rain events divergence values range from $-4x10^{-6}$ s^{-1} to $<-12x10^{-6}$ s^{-1}. The divergence value at the time after the event indicates an increase of up to $>12x10^{-6}$ s^{-1} at 300 hPa layer in Grell 3-D scheme, but in BMJ scheme the divergence value is still dominantly negative in the lower layer to the middle ($-4x10^{-6}$ s^{-1} to $0x10^{-6}$ s^{-1}). In general, the value of divergence after the incident has begun to increase, so this indicates that the convective clouds have started to stop at 23:00 UTC. The increasingly negative value at the time of the incident is an indication of a compression of the air mass is getting stronger or convergence that causes the lifting of the air mass and the formation of a strong cloud.

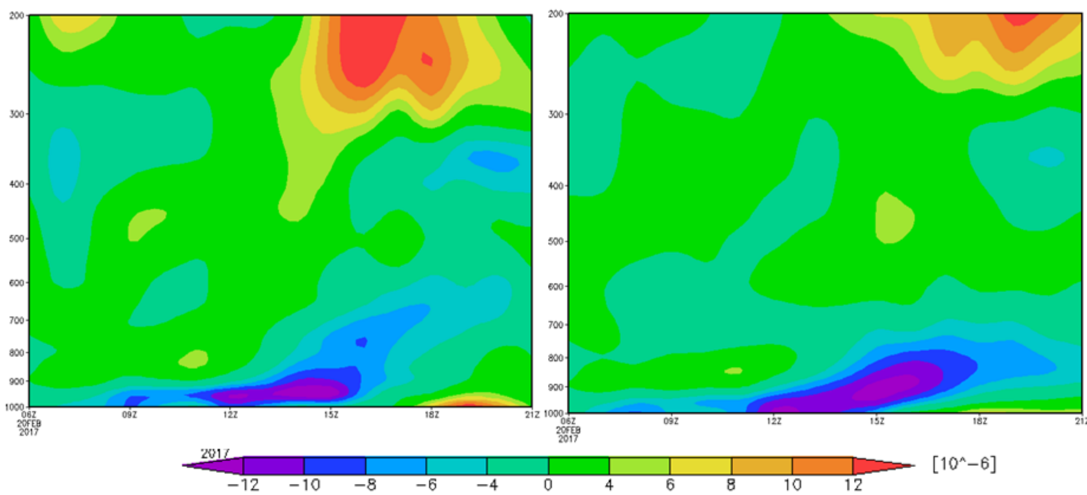

Fig. 5. Divergence layer from 1000 hPa to 200 hPa on 20th, 2017 [Left] BMJ 6 km and [Right] Grell 3-D 6 km.

While in layers 500-200 hPa on before, during, and after the event generally has divergence values in the range from $0x10^{-6}$ s^{-1} to $>12x10^{-6}$ s^{-1}. This positive value indicates that the coating occurs air or divergence periods. The existence of convergence in the lower layer (convergence) and divergence in the upper layer is a condition that is very supportive for the growth of convective clouds due to the rising air which is an indicator of a significant weather system.

3.4.2. Streamline

Based on the mapping of the 925 hPa streamline from the model output, the presence of confluence area of air mass accompanied by the weakening of wind velocity in this layer in the south-eastern part of Lampung at 12:00 UTC which is the initial stage in the growth of convective clouds in this region. Wind speed slows down to 1 m/s to 2 m/s at 12:00 UTC so that the convergence occurs at 925 hPa layer. This indicates that in this region there is a collection of air periods that support the growth of convective clouds in south-eastern Lampung that will lead to heavy rainfall. Then at 18:00 UTC seen wind speed has begun to increase to reach 11 m/s. In addition, the convergence pattern is no longer visible, indicating that the convective clouds in this region have entered the period of extinction. The outputs of both schemes have similar wind patterns.

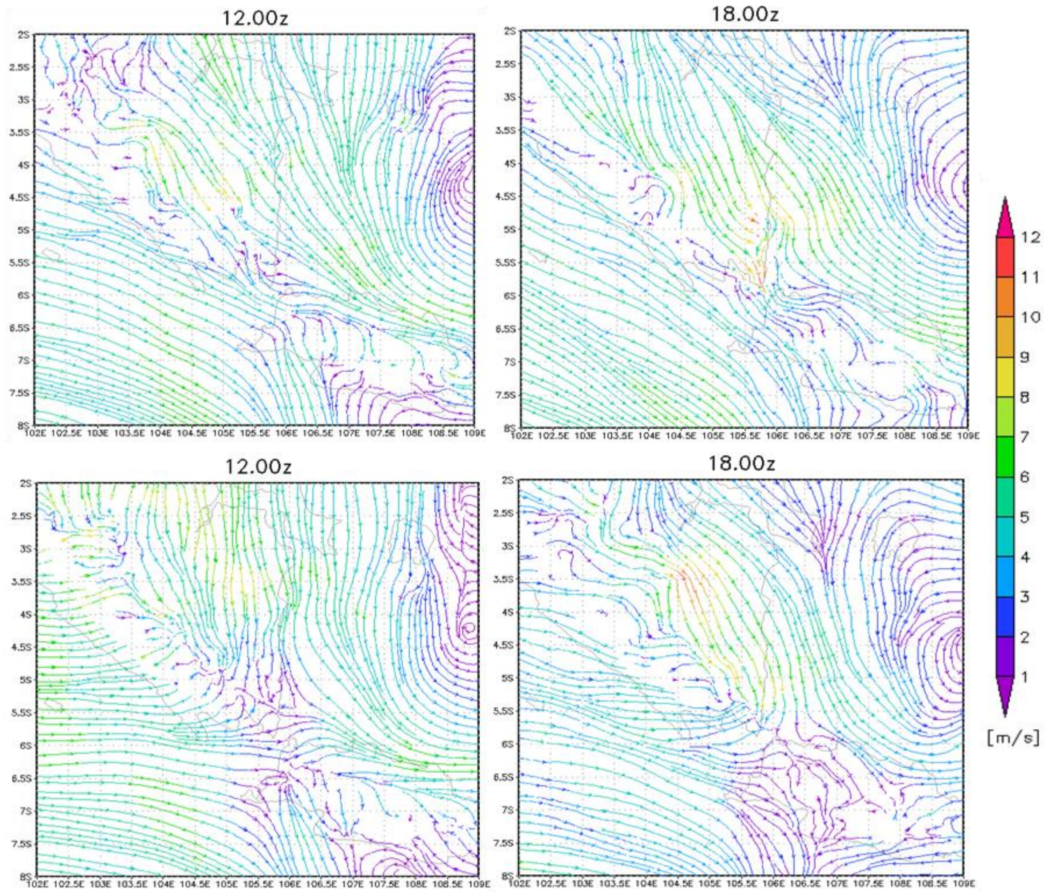

Fig. 6. Mapping of the wind field (streamline) on 20 February 2017 results of model output with a resolution of 6 km. [Top Left] BMJ at 12:00 UTC, [Top Right] BMJ at 18:00 UTC, [Bottom Left] Grell-3D at 12:00 UTC and [Bottom Right] Grell-3D at 18:00 UTC.

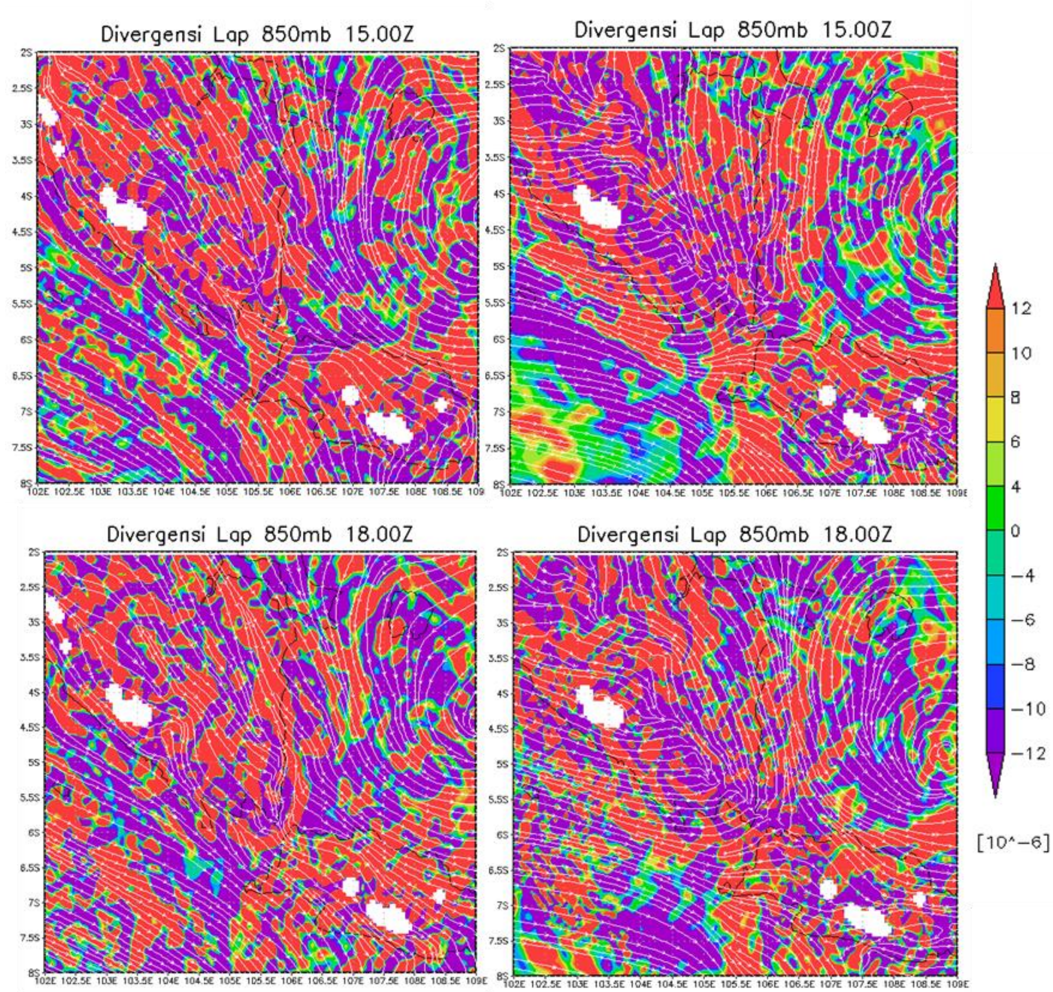

Fig. 7. Mapping of the overlay of the wind field (streamline) and divergence on 20 February 2017 results of model output with a resolution of 6 km. [Top Left] BMJ at 15:00 UTC, [Top Right] Grell-3D at 15.00 UTC, [Bottom Left] BMJ at 18:00 UTC and [Bottom Right] Grell-3D at 18.00 UTC

3.4.3. Vorticity

Vorticity can be interpreted as a micro-scale rotation. When a negative (positive) vorticity in the Southern Hemisphere signifies a cyclonic (anti-cyclonic) rotation and vice versa in the Northern Hemisphere. Figure 8 describes the change in the value of vortices before, during, and after events. Vortices start negative at 12:00 UTC until 21:00 UTC at layer 1000-600 hPa. This negative value indicates the existence of air cyclone rotation in the Lampung region, causing an increase in air period. This allows the growth of convective clouds that can cause heavy rain in this region. Stronger negative vorticity values in the lower to medium layer on the output of Grell-3D scheme. However, in the BMJ scheme, stronger negative vorticity values occur in the upper layers.

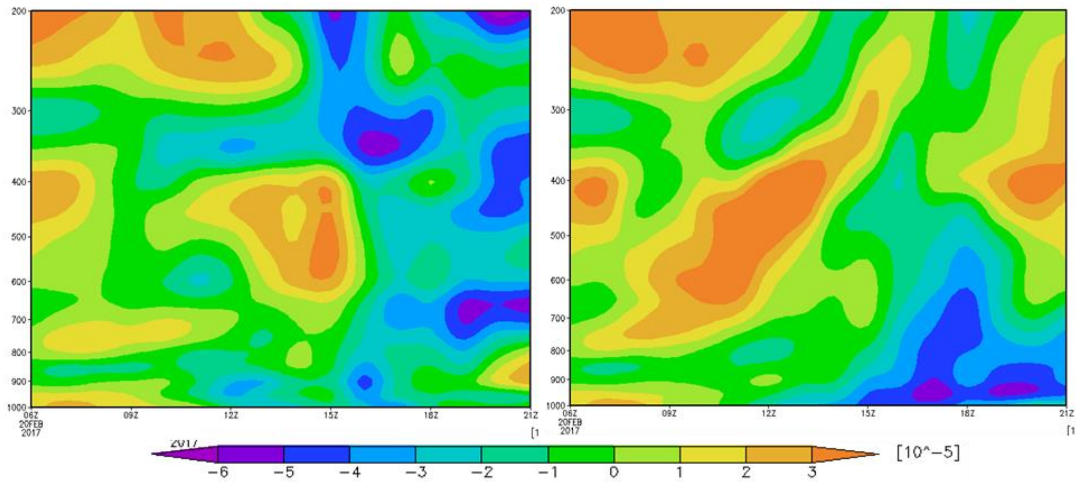

Fig. 8. Time series of vorticity data results of model output on 20 February 2017 [Left] BMJ and [Right] Grell-3D

3.4.4. Relative Humidity (RH)

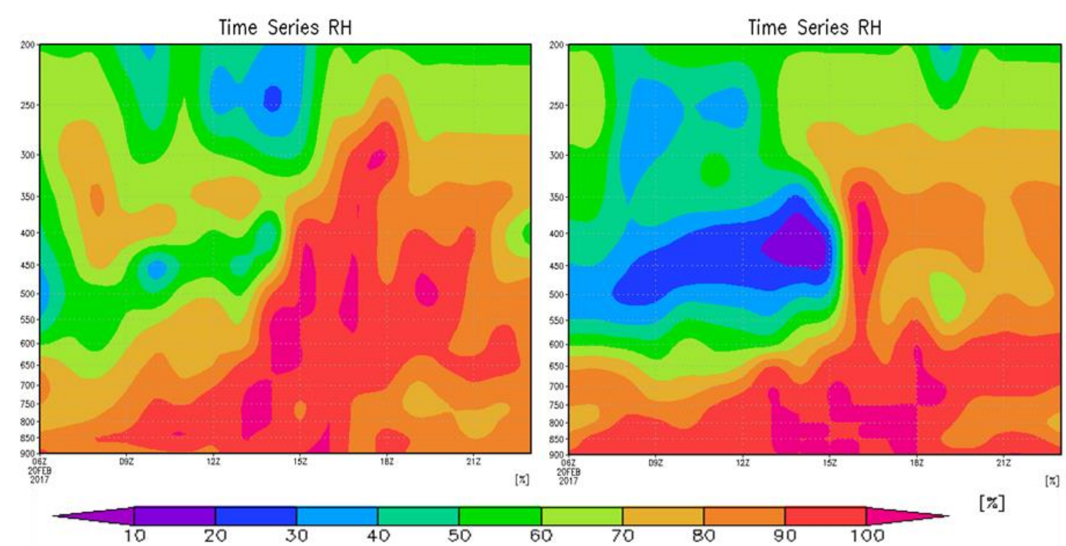

Fig. 9. Vertical profile of relative humidity result of model output on 20 February 2017 [Left] BMJ and [Right] Grell-3D

Generally, environmental conditions at the time before until after the occurrence of heavy rains is very wet with RH values ranging from 70-100% in layers 1000 hPa to 200 hPa. The humidity value of the intermediate layer begins to weigh the rise at 12:00 UTC which is the initial phase of convective cloud growth. From both schemes, the indicated humidity values differ in the intermediate layer at 09:00 UTC to 15:00 UTC, where the Grell-3D humidity scheme is low up to 20%, while in BMJ scheme the moisture value is still a quite wet which is about 50%.

3.4.5. Updraft and Downdraft Profile Simulations

The model simulation of updraft and downdraft relating to heavy rain events caused by MCC in Lampung region is shown in Figure 9 for both cumulus schemes. If compared then there will be a time difference when there is a very strong downdraft between BMJ scheme and Grell-3D scheme. On a strong downdraft, BMJ scheme starts at 13:00 UTC at 800-500 hPa and continues to peak at 17:00 UTC at layer 600-200 hPa. While in the Grell-3D scheme, strong downdraft occurs at 14:00 UTC to 18:00 UTC at the bottom layer up. However, in both schemes, it is dominated by the downdraft. As for updraft only occurs at some short time, however, the updraft incident on BMJ has more intensity compared to the Grell-3D scheme.

If related to the occurrence of heavy rain on 20 February 2017, the rain starts at 12:00 UTC and reaches its maximum value at 14.00 UTC and 15.00 UTC. Where the downdraft is related to the flow or downside of the cloud system, so it can be said that at the time of the occurrence of heavy rain is when the value of downdraft is high. So, based on the statement the most scheme is Grell-3D because of the strong downdraft at around 14:00 UTC which coincides with the occurrence of rain that reaches the maximum value.

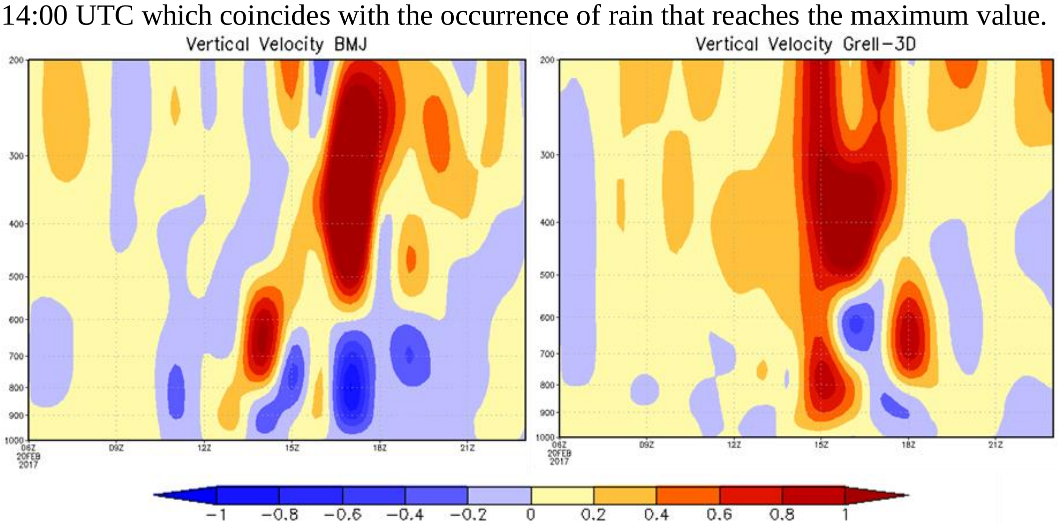

Fig. 10. Time series of vertical velocity (m/s) model simulation in time series over Lampung area on 20 February 2017 [Left] BMJ and [Right] Grell-3D

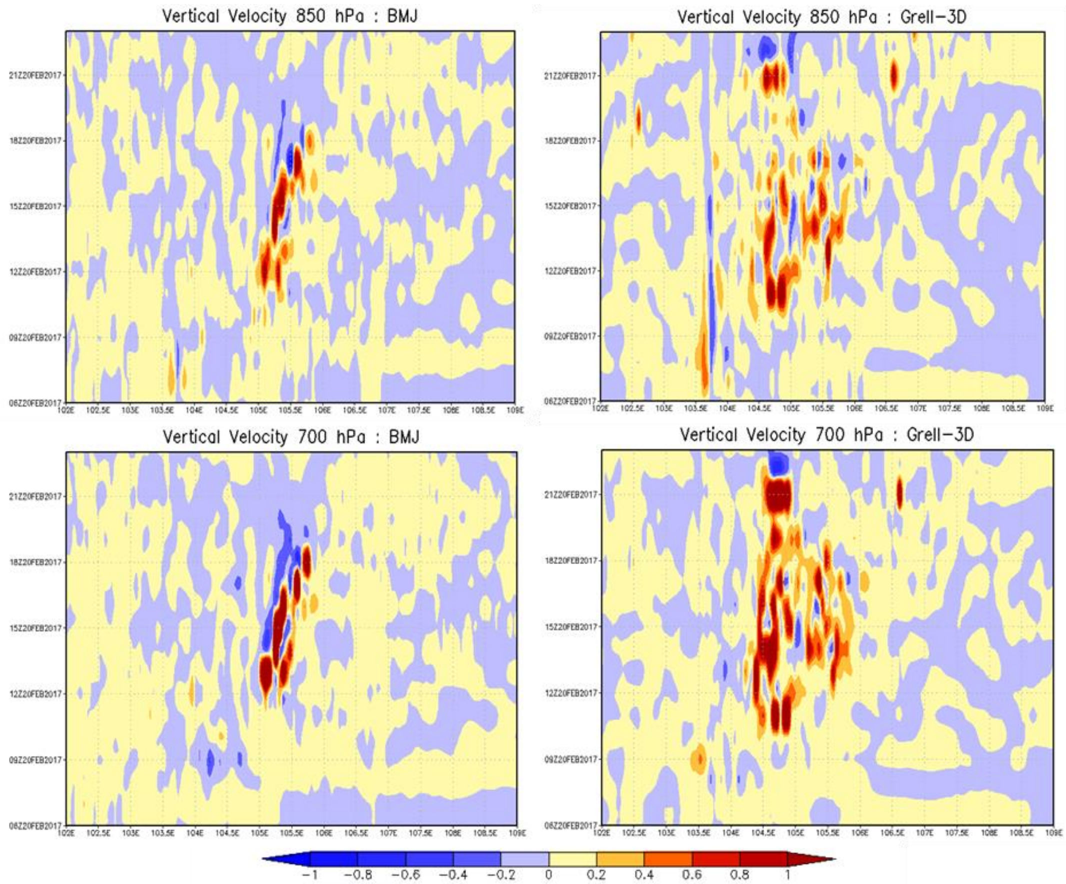

Fig. 11. Time-longitude of vertical velocity over Lampung area on 20 February 2017 [Top Left] layer 850 hPa of BMJ, [Top Right] layer 850 hPa of Grell-3D, [Bottom Left] layer 700 hPa of BMJ and [Bottom Right] layer 700 hPa of Grell-3D

Figure 11 shows the presence of vertical velocity at lais 850 hPa and 700 hPa. The area of updraft and downdraft is more concentrated on the BMJ scheme that is located in the longitude 105E to 105.5E with an intensity increasingly strong at 700 hPa layer. In the BMJ scheme clearly visible downdraft accompanied by updraft left side. While in the Grell-3D scheme, updraft and downdraft locations spread over longitude 104.5E to 105.5E and the intensity is also stronger at 700 hPa layer but with longer incidence time than BMJ scheme.

3.4.6. CAPE Simulation of BMJ and Grell-3D Schemes

Convective Available Potential Energy (CAPE) is the amount of energy that the air parcel as if it is lifted vertically at a certain distance in the atmosphere. The CAPE value is one of the indications of convective potential and signifies the condition of the atmosphere in an unstable state. The value of CAPE is expressed in units of J/kg.

Based on the WRF-ARW output data above shown that the BMJ and Grell-3D cumulus schemes have a not so big difference. Generally, the Grell-3D scheme has a larger CAPE value than the CAPE in the BMJ scheme. However, both values show considerable value, making it possible for convective clouds to form.

4. Conclusion

Based on the comparison of both the Betts-Miller-Janjic and Grell-3D cumulus schemes, it can be concluded that heavy rain in Lampung region is due to the very high humidity value from noon (intermediate surface layer) to the night (surface layer up), the value is above 90%. This condition is observed by both the results of the Betts-Miller-Janjic and Grell-3D cumulus schemes. In addition, the incidence of heavy rain is also supported by the presence of convergence areas in Lampung region with low wind speed (<10 knots), negative vorticity values that indicate the presence of rising air currents, as well as high CAPE values.

Based on spatial verification of the daily rainfall from the Betts-Miller-Janjic and Grell-3D cumulus schemes, the scheme that approximates the true condition of the GSMaP rain distribution is the Betts-Miller-Janjic scheme with a 6 km resolution which the distribution of dense rain events only concentrates on the Lampung region alone. However, when verified using statistics that is about the accuracy of the occurrence of rain every hour, the Grell-3D scheme with a resolution of 18 km and 6 km has a better result compared to Betts-Miller-Janjic scheme. Where the accuracy value of Grell-3D 18 km scheme reaches 90% while Grell-3D 6 km reach 80%, but Grell-3D 6 km scheme has perfect False Alarm Ratio and 1,25 bias value. However, when compared to the accuracy of the downdraft event of the model output with the maximum rainfall event, the most graffiti scheme is the Grell-3D scheme where downdraft events at 14:00 UTC coincide with the maximum rainfall occurrence in GSMaP. So it can be concluded that a more suitable scheme to simulate the heavy rain on 20 February 2017 in Lampung region is Grell-3D cumulus scheme.

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