WRF-model sensitivity test and assimilation studies of Cempaka tropical cyclone

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Abstract. The WRF model was used to forecast the most intensive stage of Cempaka Tropical Cyclone (TC) on 27 - 29 November 2017. This study evaluates the combination of cumulus and microphysics parameterization and the efficiency of assimilation method to predict pressure values at the center of the cyclone, maximum wind speed, and cyclone track. This study tested 18 combinations of cumulus and microphysics parameterization schemes to obtain the best combination of both parameterization schemes which later on called as control model (CTL). Afterward, assimilation schemes using 3DVAR cycles of 1, 3, 6 hours, and 4DVAR, namely RUC01, RUC03, RUC06, and 4DV, were evaluated for two domains with grid size of each 30 and 10 km. GFS data of 0.25-degree and the Yogyakarta Doppler Radar data were used as the initial data and assimilation data input, respectively. The result of the parameterization test shows that there is no combination of parameterization schemes that constantly outperform all variables. However, the combination of Kain-Fritsch and Thompson can produce the best prediction of tropical cyclone track compared to other combinations. While, the RUC03 assimilation scheme was noted as the most efficient method based on the accuracy of track prediction and duration of model time integration.

1. Introduction
Cempaka Tropical Cyclone (CTC) is one of two tropical cyclone events that occurred in the end of 2017 over Indian Ocean Southern Java Island. Theoretically, a TC event is difficult to be developed in low latitude area due to the small coriolis force [1, 2]. However, according to the Meteorological, Climatological, and Geophysical Agency (BMKG) Indonesia, CTC initiated as tropical depression on 25 November 2017 and ready as tropical cyclone phase on 27 November 2017. The lowest MSL pressure of Cempaka Tropical Cyclone hits the number of 998 millibars (mb) with a maximum wind speed of 35 knots.

CTC event delivered heavy rain and strong winds [3] in almost all regions of Java Island [4]. According to a report from the National Disaster Management Agency (BNPB) Indonesia, there are 28 districts/cities on Java Island that were affected in which 28 people died and 14,000 more people had to flee. A prediction tropical cyclone generally utilize numerical weather modeling. This is because the predictability of tropical cyclones covers a global scale with a distance of hundreds of kilometers with temporal time scale from three to ten days [5]. However, the more extended numerical weather prediction (NWP) time integration, the bigger its error grown due to the butterfly effect [6]. To reduce the error generated by NWP, we can improve initial conditions through assimilation techniques [7].
Method of assimilation varies based on its approaches such as Ensemble Data Assimilation, Monte Carlo, and Variational Data Assimilation (DVAR). Among those methods, the variational method is widely used because it has simple equations and way much cheaper to compute. The variational method consists of the 3DVAR and 4DVAR assimilation techniques. 3DVAR assimilation technique is a technique in limited area model that can be applied at mesoscale scale by taking into account multi-resolution and nested systems [8]. Meanwhile, the 4DVAR assimilation technique is the same as 3DVAR but can to assimilate data by dimension of time and requires a higher computational costs [7].

### Table 1. Combination schemes of cumulus and microphysics parameterization

| Scheme | Cumulus | Microphysics | Scheme | Cumulus | Microphysics |
|--------|---------|---------------|--------|---------|---------------|
| 1      | KF      | Kessler       | 10     | BMJ     | Ferrier       |
| 2      | KF      | Perdue Lin    | 11     | BMJ     | Goddard       |
| 3      | KF      | WSM3          | 12     | BMJ     | Thompson      |
| 4      | KF      | Ferrier       | 13     | G3D     | Kessler       |
| 5      | KF      | Goddard       | 14     | G3D     | Perdue Lin    |
| 6      | KF      | Thompson      | 15     | G3D     | WSM3          |
| 7      | BMJ     | Kessler       | 16     | G3D     | Ferrier       |
| 8      | BMJ     | Perdue Lin    | 17     | G3D     | Goddard       |
| 9      | BMJ     | WSM3          | 18     | G3D     | Thompson      |

The shortcomings of 3DVAR in accommodating assimilation can be reduced by using the rapid update cycle (3DVAR-RUC) method. The RUC method is done by adding the observation data for every cycle time adjust to the WRF spin-up time. The RUC method is believed to be able to improve the assimilation of 3DVAR which has been less than optimal because it does not take into account the dimension of time [9]. In contrast the 4DVAR assimilation technique is able assimilate data with high time density data [10].

The application of assimilation techniques for prediction and simulation of tropical cyclones, especially the prediction of tracks and physical variables such as pressure, wind direction and speed of the cyclone has been widely carried out. For instance, a study using the DVAR assimilation technique was successfully conducted by Rayhun et al. [11] and Peng and Chang [12], who tried to simulate the track and pressure variables from Tropical Cyclones Bijli and Flo. The development of the 3DVAR assimilation technique, namely 3DVAR-RUC, has also been implemented by Kumar et al. [13] to simulate a track of Tropical Cyclone Phailin. Each technique shows a significant improvement to simulate TC’s track to be compared to a model without applying assimilation techniques.

From the research that has been done regarding the prediction and simulation of tropical cyclones, not many studies have used the 3DVAR-RUC and 4DVAR assimilation techniques by utilizing radar data, especially in Indonesia. This is because tropical cyclones are rarely observed by weather radar. According to Ivanov et al. [14], radar data is more well-performed when compared to synoptic and rason observation data, as well as remote sensing such as satellites due its high spatiotemporal. Radar data provides atmospheric conditions per layer of wind data (radial velocity) and cloud microphysics (reflectivity). The ability of radar data to accommodate spatiotemporal data with high resolution is suitable to predict precipitation patterns at the mesoscale scale.
The prediction of the WRF model is also influenced by the parameterization scheme used in NWP model [15, 16]. Research conducted by Choudhury and Das [5], explains that the selection of microphysics parameterization affects the predicted results of tropical cyclone intensity, especially its center pressure variable, maximum wind speed and tracks of tropical cyclones. Also, research by Sandeep et al. [6], shows that cumulus parameterization affects the predicted results of tracks, intensity, and area of tropical cyclone eye.

Therefore, this study assesses the performance of the WRF model with the best combination of parameterization schemes using the 3DVAR-RUC and 4DVAR assimilation technique with radar data based on model efficiency.

![Figure 1](image)

**Figure 1.** The domain of the research area

### 2. Experimental design

This study applied 18 combinations of cumulus and microphysics parameterization schemes based on studies conducted by Choudhury et al., and Srinivas et al. [5, 17]. The combination of parameterization schemes is shown in Table 1. The WRF model version 3.9.1 is used to carry out the prediction. There are 2 domains with a resolution of 30 km and 10 km (Figure 1). The coverage area of Radar Yogyakarta has a radius of 250 km which includes the path traversed by CTC. Global Forecasting System (GFS) data is used as the initial condition and boundary data with a resolution of 0.25° x 0.25°. Model is integrated for 120 hours starting from November 25 2017 for each scheme.

The best combination parameterization scheme is then used as a control scheme (CTL)scheme in which will be carried out for RUC and 4DVAR assimilation methods. Afterward, the skill score is used to determine which assimilation scheme is more efficient for predicting CTC’s tracks. To verify the results of model predictions, we use press release data from CTC issued by the Meteorological, Climatological, and Geophysical Agency (BMKG).

Verification is carried out by taking into account the root mean square error (RMSE), correlation coefficient (CORR), and standard deviation (SD) for CTC air pressure and its maximum wind speed. To verify assess the track predictions, direct position error (DPE), along-track error (ATE), and cross-track error (CTE) are utilized (Figure 2). The efficiency of each scheme will be determined by the length of the time used to integrated the model and its accuracy from the verification results.
3. Result and discussion

3.1. The Effect of Cumulus and Microphysics Parameterization Schemes on the Prediction of Cyclone Tracks, Pressure Variables at the Cyclone Center and Maximum Wind Speed

Direct position error (DPE) measures the discrepancy of the low-pressure center point from the point of observation release by BMKG every 6 hours of observation. The average DPE results for each scheme can be seen in Figure 3. The average DPE is in the range of values 96.65 - 157.23 km. The smallest average DPE value is shown by scheme 12 and the largest value is shown by scheme 18. These results indicate that scheme 12 in predicting CTC tracks has smaller average error when compared to the model results from the other parameterization scheme. The variation in the average DPE value shows that the selection of the parameterization scheme used in the model affects the DPE prediction.
Based on the results of the Taylor diagram for pressure variable value (Figure 4a), it is known that the scheme 18 is outperforms in predicting the pressure variable at the cyclone center. However this scheme is unable to produce a more accurate prediction of the location of the center of low-pressure when compared to other parameterization schemes. The same results also seen for maximum wind speed, in which scheme 18 outperforms than others (Figure 4b). Yet, this scheme cannot produce the cyclone location points precisely when compared to scheme12.

![Taylor diagrams](image)

**Figure 4.** Taylor diagram test results of the cumulus and microphysics parameterization scheme of the pressure variable at the center of CTC (a) and maximum wind speed variable (b), the red dot shows the variation index of the parameterization scheme used, the orange dot shows the best results

### 3.2. Selection of the Best Parameterization Scheme

From the parameterization assessment, it is found that the best parameterization scheme act differently for each variable of pressure at the center of the cyclone, the maximum wind speed, and the track of the cyclone. However, among the 18 schemes, there is no combination scheme which outperform for all variables. Therefore, to get the best combination, we use the cyclone track following the recommendation of Burton and Burton [19]. This because cyclone tracks can be utilized to inform the public in order to carry out prevention or mitigation efforts in areas that will be affected by a cyclone event.

From the results of the parameterized assessment, it is known that scheme 12 is the best scheme for track prediction. Thus this scheme will then be used as a control scheme (CTL) to be compared with other schemes that apply assimilation methods.

### 3.3. The Results of the WRF Model of the Best Parameterization Scheme Using the Multi Assimilation Technique of Radar Yogyakarta Data on the Prediction of Cyclone Tracks

Each of the assimilation schemes was successful in predicting CTC’s track as shown in Figure 5. To find out the prediction error value of CTC track by the model for each assimilation scheme, it can use the DPE value. It measures the distance between the low-pressure center point from the model results of each assimilation scheme and the press release observation by BMKG. The result shows that the average DPE value for each assimilation scheme is in the range of values 70.4 - 128.3 km (Figure 6). The smallest average DPE value is produced by RUC03 scheme, whilst the largest average DPE value is drawn by RUC01 scheme. The RUC03 scheme even predict the smaller DPE than the CTL. It shows that the assimilation of radar data on the model has an influence on the track prediction results.
Figure 5. Cempaka Tropical Cyclone Tracks from the model results with the multi-assimilation technique, the circle mark shows the starting point of the cyclone.

Figure 6. The plot of the average direct position error (DPE) value of the assimilation scheme test results during the 120-hour forecast.

The average ATE values for each assimilation scheme are in the range of values -38.2 - 37.8 km (Figure 7a). The smallest ATE value is generated by 4DV scheme and the largest one produced by RUC01 scheme. The negative value of the ATE shows that the model predicts the track from
the cyclone produces a lower pressure center point position that is slower than the BMKG press release observation data per 6 hours interval, while the plus value shows that the model predicts the position of the low-pressure point faster than the BMKG press release observation data.

![Figure 7](image.png)

**Figure 7.** Plot the bar average value (a) along-track error (ATE) and (b) cross-track error (CTE) test results of the assimilation scheme for 120 hours of the forecast

It can be seen from Figure 7b that the average CTE values are in the range of -24.9 - 19.8 km. The smallest CTE value is generated by a model with the CTL scheme and the largest CTE value is generated by a model with the RUC01 scheme. The negative value on CTE shows that the model produces low-pressure center point tend to shifted to east and southeast compared to BMKG press release observation data and vice versa.

**Table 2.** Skill score and integration time of the assimilation scheme model.

| Assimilation Scheme | Integration Time (minutes) | Skill Score(%) |
|---------------------|---------------------------|----------------|
| RUC01               | 105                       | -32.9          |
| RUC03               | 90                        | 27.1           |
| RUC06               | 50                        | -23.4          |
| 4DV                 | 140                       | -2.3           |

The used assimilation methods delivers a significant difference on TC prediction. The utilized data also determine the quality of the TC forecast. Unfortunately the radar data used in this study has not same data size. This results each data does not capture the same number of moments or data by weather radar so this will affect the results of the assimilation model. Nonetheless, Sun [20] explained that the prediction results of an assimilationed model depends size and quality of data used.

The amount of assimilated and the techniques used in the model will determine the length of the integration time. Table 2 shows that the integration time of the assimilation scheme model varies between 50 - 140 minutes. The shortest integration time is generated by the RUC06 scheme while the longest integration time is generated by the 4DV scheme. The integration time generated by the RUC03 scheme is in an intermediate position, that is, it does not require the least time or the most.
The result of calculated skill score for each assimilation scheme, shows the variation in the range of (-32.9) - 27.1% (Table 2). The lowest skill score is generated by the RUC01 scheme, while the highest skill score is generated by the RUC03 scheme. The lowest skill score showsthat the assimilation scheme shows a decrease in accuracy by 32.9%. Whilst, the highest skill score indicated that there is an increase in accuracy in cyclonic tracks predicting by 27.1%.

Based on the skill score and model integration time, it is known that the RUC03 scheme is the most efficient scheme when compared to other assimilation schemes. Therefore, the RUC03 scheme should be considered for operational purpose.

4. Conclusion
Based on the results and discussion in the previous chapter it can be concluded that:

- The best combination for cumulus and microphysics parameterization schemes is scheme 12 which use the Betts-Miller-Janic (BMJ) cumulus scheme and the Thompson Scheme microphysics scheme. This combination produces a better predictive value of the track variables compared to other schemes.

- The RUC03 assimilation scheme is the most efficient scheme based on its accuracy value and the time used for integration.

5. References
[1] Stull R 2015 An algebra-based survey of atmospheric science. University of British Columbia, Columbia
[2] Surinati D and Kusuma D A 2018 OSEANA 43 1–12
[3] Fatkhuroyan F 2019 Perbandingan sebaran curah hujan hasil observasi satelit gpm dengan model cuaca wrf (studii kasus: Siklon tropis cempaka dan dahlia, 27 nov–3 des 2017) Seminar Nasional Geomatika vol 3 pp 1063–1070
[4] Fibriantika E 2019 Jurnal Meteorologi dan Geofisika 19 49–58
[5] Choudhury D and Das S 2017 Journal of Earth System Science 126 1–10
[6] Sandeep Č, Krishnamoorthy C and Balaji C 2018 Curr. Sci 115 1143–1153
[7] Bannister R 2017 Quarterly Journal of the Royal Meteorological Society 143 607–633
[8] Barker D M, Huang W, Guo Y R, Bourgeois A and Xiao Q 2004 Monthly Weather Review 132 897–914
[9] Payne T 2017 Tellus A: Dynamic Meteorology and Oceanography 69 1409061
[10] Huang X Y, Xiao Q, Barker D M, Zhang X, Michalakes J, Huang W, Henderson T, Bray J, Chen Y, Ma Z et al. 2009 Monthly Weather Review 137 299–314
[11] Rayhun K Z, Quadir D, Chowdhury M M, Ahsan M and Haque M 2015 Journal of Bangladesh Academy of Sciences 39 157–167
[12] Peng M S and Chang S W 1996 Monthly weather review 124 1181–1198
[13] Kumar S, Routray A, Tiwari G, Chauhan R and Jain I 2017 Simulation of tropical cyclone ‘phailin’ using wrf modeling system Tropical Cyclone Activity over the North Indian Ocean (Springer) pp 307–316
[14] Ivanov S, Michaelides S and Ruban I 2018 Remote sensing 10 1453
[15] Li J, Ping F, Zhou S and Shen X 2019 Atmospheric Science Letters 20 e875
[16] Schwitalla T, Branch O and Wulfmeyer V 2020 Quarterly Journal of the Royal Meteorological Society 146 846–869
[17] Srinivas C, Bhaskar Rao D, Yesubabu V, Baskaran R and Venkatraman B 2013 Quarterly Journal of the Royal Meteorological Society 139 1810–1825
[18] WMO 2014 Verification methods for tropical cyclone forecasts URL https://community.wmo.int/
[19] Burton H H and Burton S D 1999 Tropical cyclone forecasting URL https://www.oas.org
[20] Sun J 2015 Radar data assimilation with wrfda URL https://www2.mmm.ucar.edu/
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