IMPROVEMENT SEROJA TROPICAL CYCLONE PREDICTION USING SATELLITE RADIANCE DATA ASSIMILATION

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ABSTRACT

Tropical cyclone prediction is essential for the process of mitigating the resulting disasters. Several numerical weather models have been developed but still produce errors in tropical cyclone predictions. Data assimilation is one method that can improve the initial condition values of numerical weather prediction models so that they can approach actual atmospheric conditions to reduce tropical cyclone prediction errors. Due to the limited meteorological parameter data used for data assimilation at the location of tropical cyclone events, most of which occur in ocean areas, satellite data is needed. Radiation data is initial data from satellite data, which is then transformed into meteorological parameter data using the radiative transfer model (RTM). The Weather Research and Forecasting (WRF) model data assimilation system (WRFDA) is an open-based numerical weather and data assimilation model that has 2 RTM options, namely the Radiative Transfer Model for TIROS Operational Vertical Sounder (RTTOV) and the Community Radiative Transfer Model (CRTM). This research uses two different RTMs to compare the prediction results of Tropical Cyclone Seroja, including minimum pressure, maximum wind speed, and trajectory. The research results show that predictions of minimum pressure, maximum wind speed, and trajectory of tropical cyclone Seroja by a numerical weather model assimilated with satellite radiation data are better than without assimilation. Furthermore, the assimilation of radiation data with RTTOV has the best accuracy in predicting the maximum wind speed and minimum pressure of tropical cyclone Seroja. Meanwhile, the assimilation of radiation data with CRTM can produce a minimum error in the trajectory of tropical cyclone Seroja. Future research requires adding satellite radiation data from various sensors and satellites.

Keywords: WRFDA, satellite radiance data, CRTM, RTTOV, tropical cyclone

1. Introduction

A Tropical cyclone is an atmospheric low-pressure system where the air pressure is below standard atmospheric pressure, and the wind rotates inward counterclockwise in the northern hemisphere and clockwise in the southern hemisphere [1]. Generally, tropical cyclones initially form in low-latitude (tropical) regions and then move and develop in mid-latitude (subtropical) regions [2]. Tropical cyclones have both direct and indirect impacts on weather in tropical regions like Indonesia. The impacts of tropical cyclones in Indonesia include strong winds, extreme rainfall, and ocean waves [3,4,5]. Recent research indicates the impact of tropical cyclone Seroja on Indonesian regions, particularly in the Nusa Tenggara region, resulted in 181 deaths and 74,222 damaged houses [6].

Therefore, predicting tropical cyclones including their movement, location, and intensity is necessary for early warning to minimize disaster impacts [7]. Numerical weather modelling is required to predict weather phenomena affecting Indonesian regions due to limitations in in-situ observation data [8].

One of the open-source numerical weather models is WRF (Weather Research and Forecasting) [9]. The use of WRF in the analysis of the Seroja cyclone has succeeded in revealing that this cyclone is related to the interaction between the intertropical convergence zone (ITCZ), the Madden-Julian Oscillation (MJO), and the equatorial Rossby wave which is characterized by the presence of a double vortex [10]. However, WRF The results of numerical weather modelling including WRF heavily depend on the quality of initial condition data as input to the model. Good initial condition values are those that closely resemble the actual weather conditions [11]. Data assimilation is one method to improve the initial condition data of numerical models by considering observational data values [12].

One type of observational data used in assimilation techniques is satellite radiation data, where 97% of satellite observation data can be used for data assimilation [13]. The process of assimilating satellite radiation data requires a radiative transfer model (RTM) to transform radiation values into meteorological parameters such as temperature and humidity, which will be used in the data assimilation process. In the WRF data assimilation software (WRFDA), there is one type of RTM: the Community Radiative Transfer Model (CRTM). Research on assimilating satellite radiation data in WRF has been conducted for predicting rainfall in Indonesian regions and has shown improved accuracy in rainfall prediction in several Indonesian regions [8,14,15]. However, the studies conducted still use the Community Radiative Transfer Model (CRTM), which is intrinsically an integral component of Weather Research and Forecasting Data Assimilation (WRFDA). Therefore, it is necessary to test the comparative impact with another RTM, namely the Radiative Transfer Model for the TIROS Operational Vertical Sounder (RTTOV).

Tropical Cyclone Seroja is a cyclone that emerged and developed in the Indonesian region, causing damage and many deaths in the Nusa Tenggara region [6,14,16]. Previous research on predicting and tracking tropical cyclone Seroja using the InaNWP Model which used WRF assimilated with several BMKG observation data. However, in this study, we employ assimilation from satellite radiance data to assess whether it yields better maximum wind speed prediction and tracking results for tropical cyclone Seroja [6].

Therefore, improving the accuracy of tropical cyclone prediction with numerical weather models is necessary to reduce impacts and minimize the risks of tropical cyclones. Assimilation techniques for satellite radiation data are one way to improve the initial conditions of numerical models. Thus, this research will test the performance improvement of numerical weather prediction with assimilation techniques for satellite radiation data with 2 RTM options: Radiative Transfer Model for TIROS Operational Vertical Sounder (RTTOV) and Community Radiative Transfer Model (CRTM) by examining the differences in accuracy in parameters such as maximum wind speed around Tropical Cyclone Seroja, minimum pressure at the center of Tropical Cyclone Seroja, and the trajectory of Tropical Cyclone Seroja before and after assimilation.

2. Methods

This research utilizes simulations with the WRF pre-processing system (WPS), which plays a role in extracting data from the GFS model grid. WRFDA is responsible for data assimilation, and WRF is responsible for running the cyclone prediction simulation [15]. Subsequently, the output data of maximum wind speed, minimum air pressure, and cyclone track are compared with cyclone data from The International Best Track Archive for Climate Stewardship (IBTrACS): https://www.ncei.noaa.gov/products/international-best-track-archive.

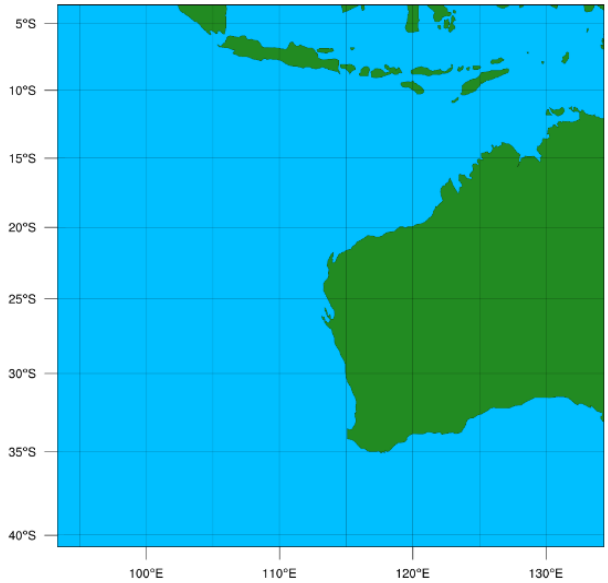

Figure 1. The Research Domain of Tropical Cyclone Seroja

Table 1. Table of WRF-ARW Model Configuration

Configuration	Domain
Latitude Center	-23,411
Longitude Center	113,837
East-West Grid Dimension	280
North-South Grid Dimension	280
Horizontal Grid Resolution	15 Km
Temporal Output Resolution	360 minutes
Geog Resolution	10 minutes
Maps projector	*Mercator*
Planetary Boundary Layer (PBL) Parameterization Scheme	Yonsei University (YSU)
Microphysics Parameterization Scheme	WRF Single Moment 6 Class Scheme (WSM6)
Cumulus Parameterization Scheme	Kain-Fritsch (KF) Scheme
Shortwave Radiation Parameterization Scheme	Rapid Radiative Transfer Model for GCMs (RRTMG)
Longwave Radiation Parameterization Scheme	Rapid Radiative Transfer Model for GCMs (RRTMG)

The simulation period aligns with the lifespan of Cyclone Seroja from April 4, 2021, at 12:00 UTC to April 12, 2021, at 06:00 UTC with output intervals every 6 hours. The research domain is depicted in Figure 1, and the WRF configuration is outlined in Table 1.

In Figure 2, the research flow is explained, where three simulations are conducted: a simulation without assimilation (NONDA), assimilation of satellite radiation data with CRTM (DA CRTM), and assimilation of satellite radiation data with RTTOV (DA RTTOV). The research domain covers the area traversed by Tropical Cyclone Seroja from its formation to its dissipation, as shown in Figure 1. Grid resolution and output are adjusted according to available computational resources. The selection of parameterization schemes for PBL, microphysics, cumulus, and longwave radiation in Table 1 is based on previous research [17,18,19] on Radiation Data Assimilation for typhoon simulation.

The following parameterization schemes are used the Yonsei University (YSU) planetary boundary layer (PBL) Parameterization scheme [20], the WRF Single Moment 6-class (WSM6) microphysics parameterization scheme [21], the Kain-Fritsch (KF) cumulus parameterization scheme [22], and the Rapid Radiative Transfer Model for GCMs (RRTMG) shortwave and longwave radiation parameterization schemes [23].

The tools used are:
1. Linux Ubuntu version 18.03 operating system.
2. Fedora version 34 operating system.
3. WRF-ARW and WRFDA version 4.3.1 models.
4. RTTOV version 12.3.
5. Post-processing applications including ARWpost version 3.1, GrADS, NCL, and Python version 3.10.

The data used are:
1. GFS data with a grid resolution of 0.25° x 0.25° and a temporal resolution of every 3 hours from April 4, 2021, at 00:00 UTC to April 12, 2021, at 06:00 UTC: https://data.ucar.edu/dataset/ncep-gfs-0-25-degree-global-forecast-grids-historical-archive.
2. Polar satellite radiation data from 10 sensors listed in Table 2 in BUFR format, downloaded every 00:00 UTC from April 4, 2021, to April 12, 2021: https://rda.ucar.edu/datasets/ds735.0/.
3. Default CV3 background error data is already integrated into the WRFDA package.

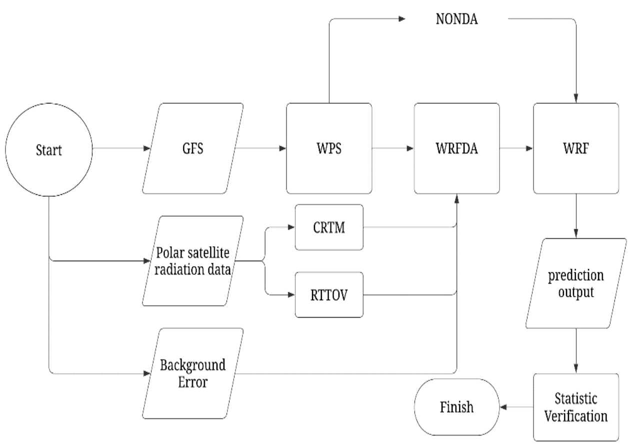

Figure 2. Flowchart

Table 2. Table of Sensors Used in Polar Satellite Data Assimilation.

Instrument	Satellite	Format	(Platform, SATID, Sensor)
AMSU-A	EOS-Aqua	BUFR	(9,2,3)
AMSU-A	METOP-A	BUFR	(10,2,3)
AMSU-A	NOAA 15, 18, dan 19	BUFR	(1,15–19,3)
HIRS-4	NOAA 18 dan 19	BUFR	(1,18–19,0)
MHS	METOP-A	BUFR	(10,2,15)
MHS	NOAA 18 dan 19	BUFR	(1,18–19,15)

Afterward, temporal analysis of the parameters of Tropical Cyclone Seroja's track will be conducted using statistical verification [24]:

1. Pearson Correlation

$$r = \frac{\sum_{i=1}^{n}(x_i . y_i)}{\sqrt{\sum_{i=1}^{n}(x_i .)^2 \sum_{i=1}^{n}(y_i)^2}} \qquad (1)$$

2. Root Mean Square Error

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad (2)$$

Explanation:

n : number data

y : model data

x : observed data

Statistical verification is performed on the track of Tropical Cyclone Seroja's output from all models against the best track data from IBTrACS by calculating the Direct Position Error (DPE) value, which measures the distance between the model output's center point and the best track data's center point at the same time using the haversine equation as shown below. For the center point of Tropical Cyclone Seroja, it is determined based on its minimum pressure [25].

$$d = 2r\ arcsin\ arcsin\ \sqrt{haversine(\emptyset^2 - \emptyset^1) + \ cos\emptyset^1 \times \ cos\emptyset^2 \times ersine(\lambda_2 - \lambda_1)} \qquad (3)$$

Explanation :

$\emptyset_1, \emptyset_2$: latitude

λ_1, λ_2 : longitude

r : earth's radius

d : distance between two points on the Earth's surface.

3. Result and Discussion

Based on Figure 3, the DA-RTTOV model output for the minimum pressure parameter shows correlation and RMSE values closer to the observation compared to the other two models. The DA-RTTOV model has a correlation value of 0.40, with an RMSE of 7.30 hPa. From the graph in Figure 3, it can be observed that the consistency of DA-CRTM and DA-RTTOV model outputs is closer to the best track data compared to the NONDA model, which exhibits significant deviations or less favorable consistency compared to DA-CRTM and DA-RTTOV.

According to Table 3, the NONDA model output has a relatively low correlation compared to the other two models, with a correlation value of 0.26 and an RMSE of 9.22 hPa for the NONDA model.

Minimum air pressure information is crucial in tropical cyclone prediction to measure the strength and lifespan of the cyclone [24,25]. RTTOV's improvement in minimum air pressure values over CRTM is attributed to CRTM's bias caused by greater hydrometeor radiation effects compared to RTTOV[26].

Based on Figure 4, the DA-CRTM model output for the maximum wind speed parameter exhibits the best correlation compared to the other two models, NONDA and DA-RTTOV. The DA-CRTM model has a correlation value of 0.34 and an RMSE of 17.40 knots. Meanwhile, for the RMSE value as seen in Figure 3, the output of the maximum wind speed parameter around the cyclone for the DA-RTTOV model shows relatively good consistency, with fewer significant deviations compared to NONDA and DA-CRTM.

Table 3. Verification Results of Correlation (CORR) and RMSE Models For Minimum Pressure at The Center Of Tropical Cyclone Seroja

Experiments	CORR	RSME (hPa)
NONDA	0.26	9,22
DA CRTM	0.29	9,82
DA RTTOV	0.40	7,30

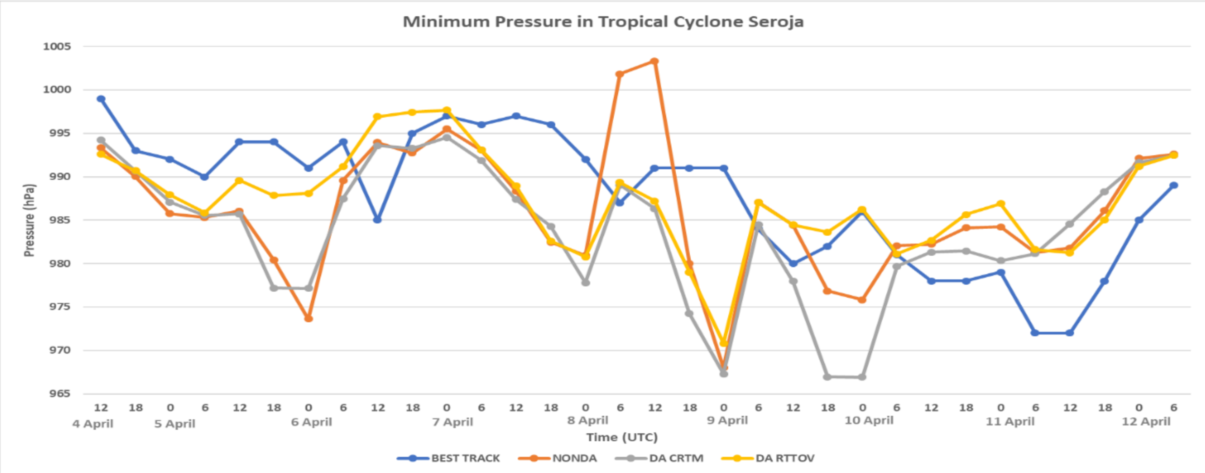

Figure 3. Depicts the time series graph of minimum air pressure at the center of Tropical Cyclone Seroja every 6 hours, derived from model outputs and best track data from April 4th to April 12th, 2021.

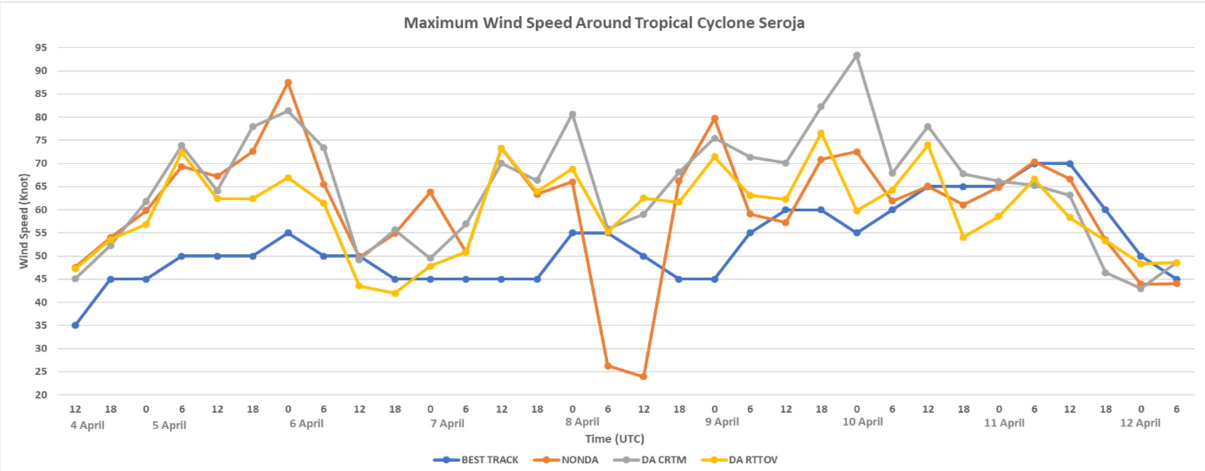

Figure 4. Time series graph of maximum wind speed around Tropical Cyclone Seroja every 6 hours, derived from model outputs and best track data from April 4th to April 12th, 2021.

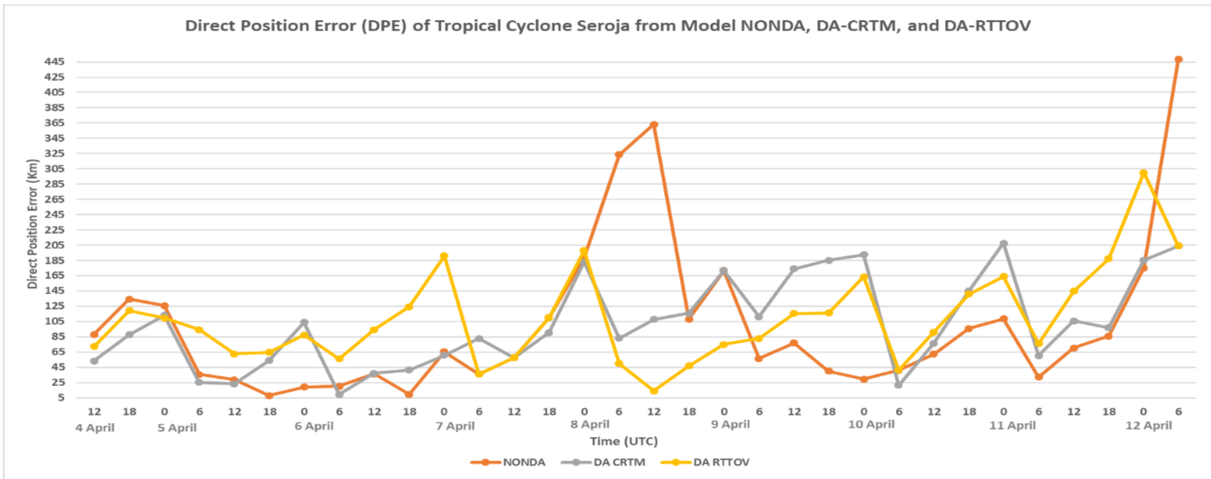

Figure 5. Time Series Graph of DPE (Direct Position Error) of Tropical Cyclone Seroja's Output from WRF NONDA, DA-CRTM, and DA-RTTOV from April 4th to April 12th, 2021

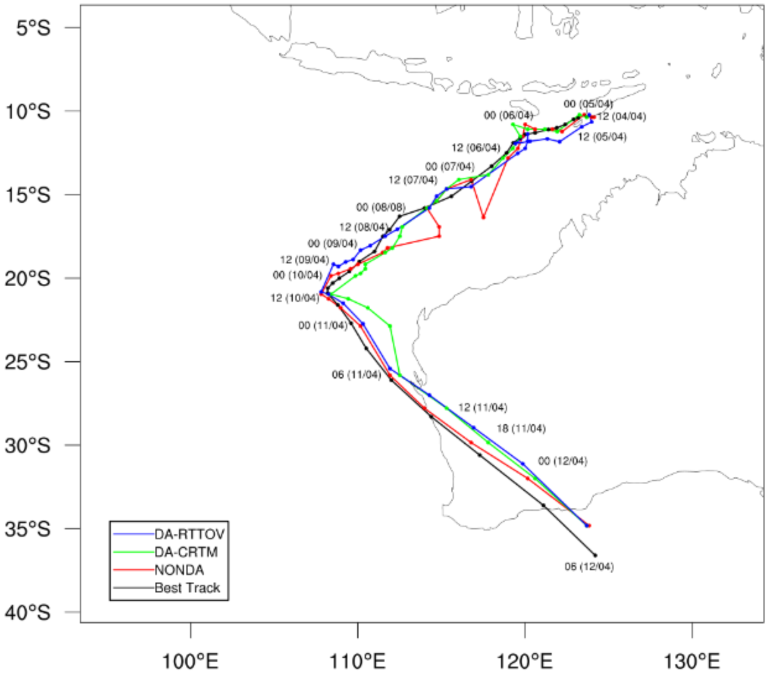

Figure 6. Track of Tropical Cyclone Seroja Output from WRF NONDA, DA-CRTM, DA-RTTOV, and Best Track Data.

Table 4. Verification results of correlation (CORR) and RMSE models for maximum wind speed around Tropical Cyclone Seroja.

Experiments	CORR	RSME (Knot)
NONDA	0.20	16,21
DA CRTM	0.34	17,40
DA RTTOV	0.33	12,32

According to Table 4, the correlation value of DA-RTTOV is not significantly different from DA-CRTM, with a value of 0.33, and an RMSE of 12.32 knots for the DA-RTTOV model. Meanwhile, relatively poor correlation values are found in the NONDA model, with a correlation value of 0.20 and an RMSE of 16.21 knots for the NONDA model. As seen in Figure 5, NONDA can be considered relatively poor due to frequent model consistency deviations from the best track data compared to the other two models. Improvement in the prediction performance of minimum air pressure and maximum wind speed of tropical cyclones after assimilating satellite radiation data with RTTOV compared to CRTM is due to CRTM's bias caused by greater hydrometeor radiation effects compared to RTTOV [16].

Based on Figure 5, which shows the DPE time series graph of Tropical Cyclone Seroja over nine days from April 4th to April 12th, 2021, with a 6-hour interval, the NONDA model output experiences a minimum DPE value of 7.9 km on April 5th, 2021, at 18:00 UTC. For the DA-CRTM model output, the minimum DPE value is 9.6 km on April 6th, 2021, at 06:00

UTC. Meanwhile, for the DA-RTTOV model output, the minimum DPE value is 14.1 km on April 8th, 2021, at 12:00 UTC.

For the NONDA model output, the maximum DPE value is 448.4 km on April 12th, 2021, at 06:00 UTC. For the DA-CRTM model output, the maximum DPE value is 107.4 km on April 11th, 2021, at 00:00 UTC. Meanwhile, for the DA-RTTOV model output, the maximum DPE value is 299.9 km on April 12th, 2021, at 00:00 UTC. Thus, it can be observed that the model output with significant deviations is produced by NONDA, while the model output with a narrower range is produced by DA-CRTM.

In Figure 6, the consistency of the model outputs for the track of Tropical Cyclone Seroja between the NONDA, DA-CRTM, and DA-RTTOV outputs with the best track data can be observed. The DA-RTTOV model output closely follows the best track, while the NONDA model output significantly deviates from the best track, indicating significant deviations caused by NONDA's exclusion of satellite observation data, unlike DA-CRTM and DA-RTTOV.

4. Conclusion

Based on the analysis and discussion conducted, we conclude that overall, the assimilated model outputs can improve to approximate observations, with DA-CRTM and DA-RTTOV having advantages in their respective parameters. For the minimum pressure parameter around Tropical Cyclone Seroja, the model with the closest correlation is DA-RTTOV, with a correlation of 0.40 and an RMSE of 7.30 hPa. DA-CRTM has a correlation of 0.29 with an RMSE of 9.82 hPa, while NONDA has a correlation of 0.26 with an RMSE of 9.22 hPa. As for the maximum wind speed around Tropical Cyclone Seroja, DA-CRTM exhibits the closest correlation to observations, with a correlation of 0.34 and an RMSE of 17.40 knots. The correlation value for DA-RTTOV is 0.33 with an RMSE of 12.32 knots, and for NONDA, the correlation is 0.20 with an RMSE of 16.21 knots.

However, the difference in correlation values between DA-CRTM and DA-RTTOV for maximum wind speed is very small, and the RMSE for DA-RTTOV is much lower than DA-CRTM. Additionally, visually, on some dates, DA-RTTOV appears to perform better than DA-CRTM in determining maximum wind speed. Regarding the track of Tropical Cyclone Seroja, the model output with the smallest deviation is produced by DA-CRTM, with a range of DPE (Direct Position Error) from 9.6 km to 107.4 km, while DA-RTTOV has a range of 14.1 km to 299.9 km, and NONDA often deviates significantly, with a range of 7.9 km to 448.4 km.

Suggestion

Based on the findings of this study, several challenges need to be addressed for future research, including:

1. This study used a horizontal grid resolution of 15 km due to computational limitations, so it would be beneficial for future research to reduce the horizontal grid resolution.
2. This study utilized the assimilation of polar satellite radiation data, so for future research, it would be beneficial to use the assimilation of geostationary satellite radiation data such as Himawari-8.
3. The data assimilation technique used in this study was 3D-Var, so there is a need to test using other techniques such as 4D-Var.

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