Geographia Technica, Vol. 20, Issue 1, pp 298 to 312

ANALYSIS OF EXTREME RAINFALL OF TROPICAL CYCLONE USING SOLAR RADIATION MANAGEMENT AND ERA5 DATA IN EASTERN PART OF INDONESIA

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DOI: 10.21163/GT_2025.201.20

ABSTRACT

The East Nusa Tenggara (NTT) and Papua provinces, located in eastern Indonesia, have recently experienced an increase in the frequency and intensity of tropical cyclones and extreme weather events. The impact of tropical cyclones in this region, particularly in terms of extreme rainfall, has raised concerns about the potential for severe flooding, landslides, and damage to infrastructure. This study aims to investigate the extreme rainfall due to tropical cyclones. We focus on three tropical cyclones (TC) that struck in eastern Indonesia, i.e., Seroja TC (April 2021), Surigae TC (April 2021), and Rai TC (December 2021). The extreme rainfall during TC was analyzed using the ERA5 model, with Bias correction from GeoMIP applied to enhance accuracy. The Solar Radiation Management (SRM) is used for comparative analysis and impact evaluation, assessing how each scenarios influence extreme rainfall during tropical cyclones by comparing GeoMIP model with ERA5 data. Our analysis using Solar Radiation Management (SRM) shows that the data from both sources correlate well and indicate a decrease in rainfall over eastern Indonesia during the tropical cyclone. Potential biases in the GeoMIP approach, such as the simplification of cloud-aerosol interactions and the assumptions underlying the SRM mechanism, may contribute to underestimating precipitation.

Key-words: *Tropical cyclone; Extreme rainfall; SRM; ERA5; Indonesia.*

1. INTRODUCTION

Tropical cyclones are intense storms marked by rotating wind patterns, developing over warm waters with vertically growing convective clouds and wind speeds of 34 knots or higher (Syaifullah, 2015). These cyclones play a crucial role in atmospheric circulation, transferring heat from the equator to higher latitudes (Ginanjar, 2020). Over a 42-year period, tropical cyclones near southern Indonesia occur most often in February, with a total of 122 events averaging 2.9 per year (Kaha et al., 2024).

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According to research by Makmur et al. (2021), at least seven notable tropical cyclones have impacted areas close to Indonesia, including Cyclone Vamei (December 26-31, 2001), Cyclone Inigo (March 30 - April 9, 2003), Cyclone Durga (April 22-24, 2008), Cyclone Kirrily (April 26-27, 2009), Cyclone Cempaka (November 26-29, 2017), Cyclone Dahlia (November 29 - December 4, 2017), and most recently, Cyclone Seroja in the Savu Sea, East Nusa Tenggara, from April 2-9, 2021, which is one of the focus of this article.

According to official statements from BMKG deputies analyzing data on cyclonic storms, Tropical Cyclone Seroja reached maximum wind speeds of about 40 knots (75 km/h), leading to severe flooding across several islands in the NTT province and Timor Leste (Welan et al., 2023). Research by Welkis et al. (2021) indicates that Cyclone Seroja could trigger extreme hydrometeorological disasters, with direct impacts including intensified rainfall, high wind speeds, and large waves. These primary effects led to secondary impacts such as flooding, landslides, erosion, disruption of coastal ecosystems, coastal flooding, and damage to infrastructure (Fang et al., 2017). Another study by Kurnia et al. (2023) reported that the disaster affected 21 cities and districts in NTT, with 629,514 people impacted, 184 fatalities, and 6,629 homes severely damaged. Extreme rainfall is generally defined as a rain event that occurs with heavy intensity or very high rainfall in a short period of time. Experts use several definitions regarding heavy rainfall resulting in extreme weather conditions. One of the most common definitions is daily rainfall that exceeds a certain threshold value. This threshold value may vary depending on a region's location and climatic conditions. According to the Meteorology, Climatology, and Geophysics Agency (BMKG), heavy rainfall is defined as daily rainfall with an intensity of at least 150 mm/day (Kiki et al., 2024)

The significant losses highlighted an urgent need for a thorough strategy to reduce risks associated with extreme weather events. Understanding how tropical cyclones interact with climate factors, including Solar Radiation Management (SRM), is essential for developing adaptive measures to lessen these impacts. SRM is a climate intervention strategy that involves techniques designed to reflect a small percentage of incoming solar radiation back into space, potentially cooling the Earth's surface and counteracting the warming effects of greenhouse gas emissions. SRM includes approaches like stratospheric aerosol injection, which disperses fine particles in the upper atmosphere to increase the Earth's albedo or reflectivity. Another method is marine cloud brightening, which seeks to enhance the reflectivity of low-lying clouds over the ocean by introducing particles that encourage cloud formation. While SRM does not reduce greenhouse gases in the atmosphere, it could, in theory, provide temporary relief from warming trends, particularly for regions experiencing climate-related extreme events like tropical cyclones.

However, the application of SRM specifically to extreme rainfall events induced by tropical cyclones remains an understudied area. Most previous studies have focused on broader climate impacts, with limited research evaluating how SRM might influence cyclone-related precipitation and disaster risks. This study addresses this gap by specifically analyzing how SRM impacts extreme rainfall caused by tropical cyclones, particularly in the context of the Indonesian region, which has not been thoroughly examined in previous studies. By utilizing data from the Geoengineering Model Intercomparison Project (GeoMIP) and the ERA5 reanalysis dataset, this research assesses the extent to which SRM scenarios influence rainfall intensity during cyclone events. The findings provide new insights into the feasibility of SRM as a potential intervention for mitigating cyclone-induced extreme rainfall and contribute to the ongoing discourse on climate intervention strategies.

2. STUDY AREA

This study focuses on the eastern region of Indonesia, as shown by the red rectangle in **figure 1**, which includes not only East Nusa Tenggara (NTT) Province and Papua Province, but also parts of Maluku and other provinces on Papua Island. This region is affected by three tropical cyclones that occurred in 2021, including: Seroja TC (April 2021), Surigae TC (2021), and Rai TC (December, 2021). East Nusa Tenggara Province (Lat: -11º – -7.5º, Lon: 117º – 126.5º) Located in southeast Indonesia, East Nusa Tenggara has a prominent wet and dry season with a unique monsoonal climate. Its complex topography and archipelagic nature contribute to diverse microclimates, making it highly susceptible to extreme weather events. Tropical Cyclone Seroja (April 2021) and Tropical Cyclone Rai (December 2021) have highlighted the province's vulnerability to intense rainfall and hydrometeorological disasters, including floods and landslides.

The province of Papua (Lat: -10º – 5º, Lon: 125º – 141º), which is in eastern Indonesia, is home to both tropical and alpine rainforests, making it one of the most diverse ecosystems on Earth. Despite receiving substantial precipitation year-round, the province faces significant climate-related risks, including shifts in rainfall patterns and threats to biodiversity. Tropical Cyclone Surigae (April 2021) underscored Papua's vulnerability to extreme weather, as it brought intense rainfall and strong winds, heightening the risk of floods, landslides, and ecosystem disturbances.

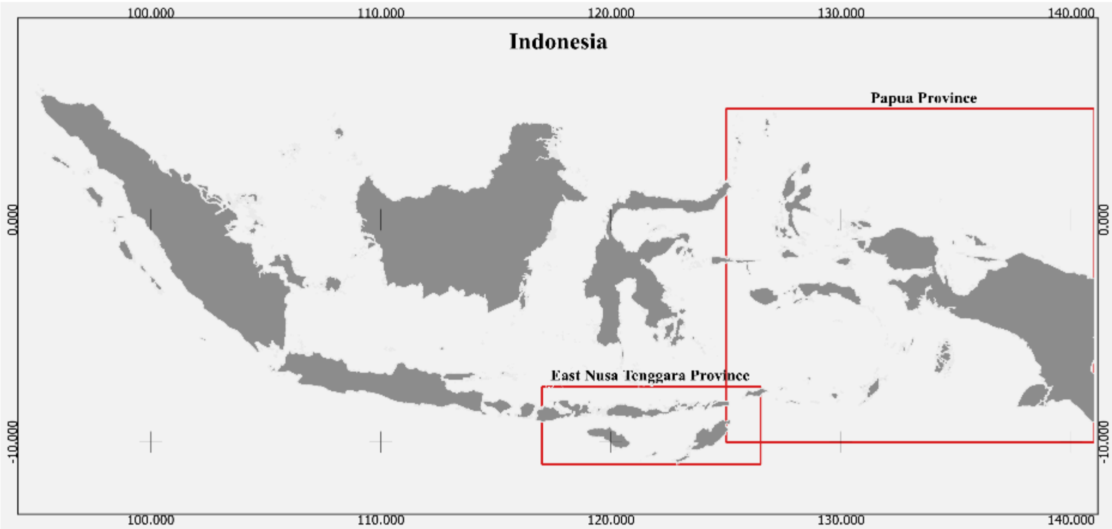


Fig. 1. Study area map showing the East Nusa Tenggara and Papua Provinces, Indonesia.

3. DATA AND METHODS

3.1. Climate Data

This study utilizes the Geoengineering Model Intercomparison Project (GeoMIP) model output data. Data from the G6solar and G6sulfur scenarios, alongside SSP2-4.5 and SSP5-8.5, are employed as outlined in Table 1. GeoMIP allows the simulation of various climate intervention scenarios, including G6solar and G6sulfur, which aim to reduce global warming through SRM. To focus on hydrometeorological extremes through daily rainfall analysis, we use the global gridded daily rainfall data from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset Funk et al. (2015) as the reference. GeoMIP is used to understand the impact of climate change on extreme rainfall during tropical cyclone events in eastern Indonesia. By comparing GeoMIP model results with observational data, this study provides insight into how climate change strategies can affect the intensity and distribution of extreme rainfall during tropical cyclone events.

Table 1.

Summary of model simulation from GeoMIP experiment used in this study.

Model Name	Variant	Resolution*	Period	References
CESM2-WACCM	r1i2p1f1	288 × 192	2015-2100	Danabasoglu (2019)
CNRM-ESM2-1	r1i1p1f2	256 × 128	2015-2100	Seferian (2019)
MPI-ESM1-2-LR	r1i1p1f1	192 × 96	2015-2100	Niemeier et al. (2019)
	r2i1p1f1			
	r3i1p1f1			

**Resolution is described as horizontal latitude × longitude described by Piani et. al. (2010).*

We also utilize data from the European Centre for Medium-Range Weather Forecasts (ECMWF) version 5, known as ERA5, which offers hourly estimates for numerous climate variables related to the atmosphere, land, and oceans. This dataset spans the entire Earth on a 30 km grid and represents the atmosphere with 137 vertical levels, extending from the surface up to 80 km in altitude (ECMWF website). We extracted data from ERA5 on the dates when the tropical cyclone passed and then compared the extreme rainfall values with data from GeoMIP.

3.2. Methods

3.2.1. ETCCDI Indices Calculation

Rainfall-based extreme indices are calculated according to definitions recommended by the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (Schmidt et al., 2012). This study examines annual maximum 1-day precipitation (Rx1Day) indices. These indices will be computed using both observed and modelled rainfall data.

3.2.2. Bias Correction

The correction factor is derived from the linear regression equation between annual extreme indices calculated from model outputs and reference data. In this study, the annual index calculated from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) dataset, with a spatial resolution of 0.05°, serves as the reference data (Funk et al., 2015).

The correction factor used fulfils the following equation:

$$Y_{obs} = a + b * X_{mod} \quad (1)$$

where a is the intercept and b is the regression slope.

This approach involves adjusting the distribution pattern of the model output dataset so it aligns with the observed data (Piani et al., 2010). In this method, both the observational and model datasets are assumed to follow a Generalized Extreme Value (GEV) distribution. The GEV distribution is commonly used to represent the probability distribution of extreme events (Rypkemaa & Tuljapurkar, 2021). It is defined by three parameters: the shape parameter (γ), the location parameter (μ), and the scale parameter (σ), as represented by the following functions:

$$F_{\sigma,\gamma,\mu}(x) = \exp\left[-\left(1 + \gamma\frac{x-\mu}{\sigma}\right)^{-1/\gamma}\right] \text{ with } 1 + \gamma\left(\frac{x-\mu}{\sigma}\right) > 0, \gamma \neq 0 \quad (2)$$

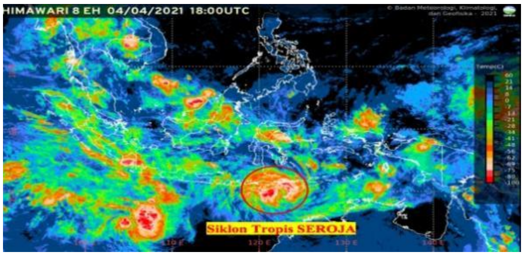
$$F_{\sigma,\gamma,\mu}(x) = \exp\left(-e^{-\frac{x-\mu}{\sigma}}\right) with\ \gamma = 0 \quad (3)$$

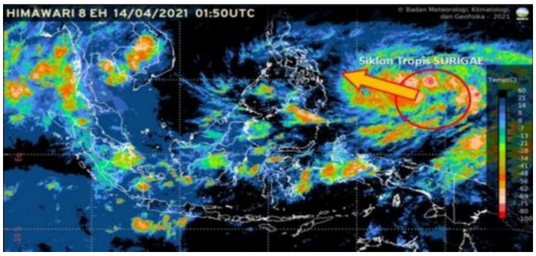
here, $\mu \in R$ and $\sigma > 0$, with the shape parameter γ determining the GEV distribution type. The three types—Fréchet, Gumbel, and Weibull (also known as types I, II, and III)—correspond to $\gamma < 0$, $\gamma = 0$, and $\gamma > 0$, respectively (Giang, 2021). The correction or transfer function (f) between model data (x) and observation data (y) is derived from the inverse cumulative distribution function (CDF) for each dataset, ensuring that y = f(x) is satisfied.

4. RESULTS AND DISCUSSIONS

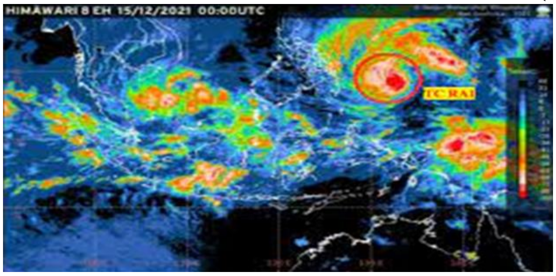
4.1. Tropical Cyclone

In 2021, there were three tropical cyclones that crossed the eastern region of Indonesia, namely Seroja, Surigae, and Rai. Tropical Cyclone has the potential to cause hydrometeorological disasters such as tornadoes, floods, landslides, hail, blizzards, heavy rain, snowfall, and extreme drought. For instance, the impact of Seroja TC on April 2 - 3, 2021, resulted in floods and landslides in 10 districts. Areas hit by floods include Kupang City, East Flores Regency, Central Malacca Regency, Lembata Regency, Ngada Regency, Alor Regency, East Sumba Regency, Rote Ndao Regency, Sabu Raijua Regency, South Central Timor Regency, and Ende Regency. The following (**Fig. 2**) are views of tropical cyclones from the Himawari satellite (BMKG Website).





(a) (b)



(c)

Fig. 2. Tropical Cyclone of Seroja (a), Surigae (b), and Rai (c) (*Source: BMKG website*).

4.2. Comparison Result

4.2.1. ERA5 Data of Seroja TC

Seroja TC crossed Indonesia on April 1-4, 2021, but the highest rainfall intensity occurred on April 3, 2021. We extracted data from ERA5 for Seroja TC on April 3, 2021, as shown in **figure 3**. The extreme rainfall intensity of Seroja TC is 50 mm/day.

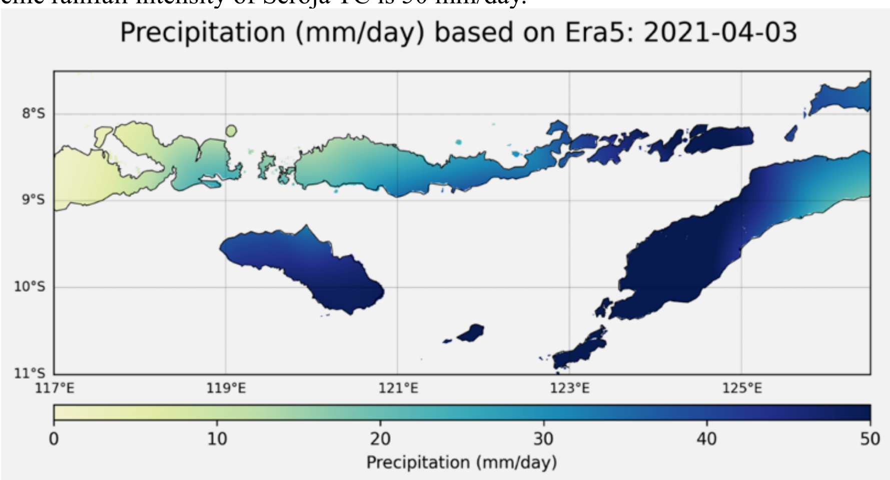


Fig. 3. The extreme rainfall of ERA5 data on 3 April 2021 from Seroja TC.

4.2.2. GeoMIP Data of Seroja TC

We also extracted data from GeoMIP on April 3, 2021, to compare ERA5 data. GeoMIP simulation model has four components, namely G6solar, G6sulfur, SSP245 and SSP585. In GeoMIP, there are five simulation models, as shown in **Table 1**, namely CESM2-WACCM (1 model), CNRM-ESM2-1 (1 model), and MPI-ESM1-2-LR (3 models). Each model has four components mentioned earlier, namely G6solar, G6sulfur, SSP245, and SSP585 (**Fig. 4**). We calculate the average from the five models and compare it with extreme rainfall data from Seroja TC from ERA5.

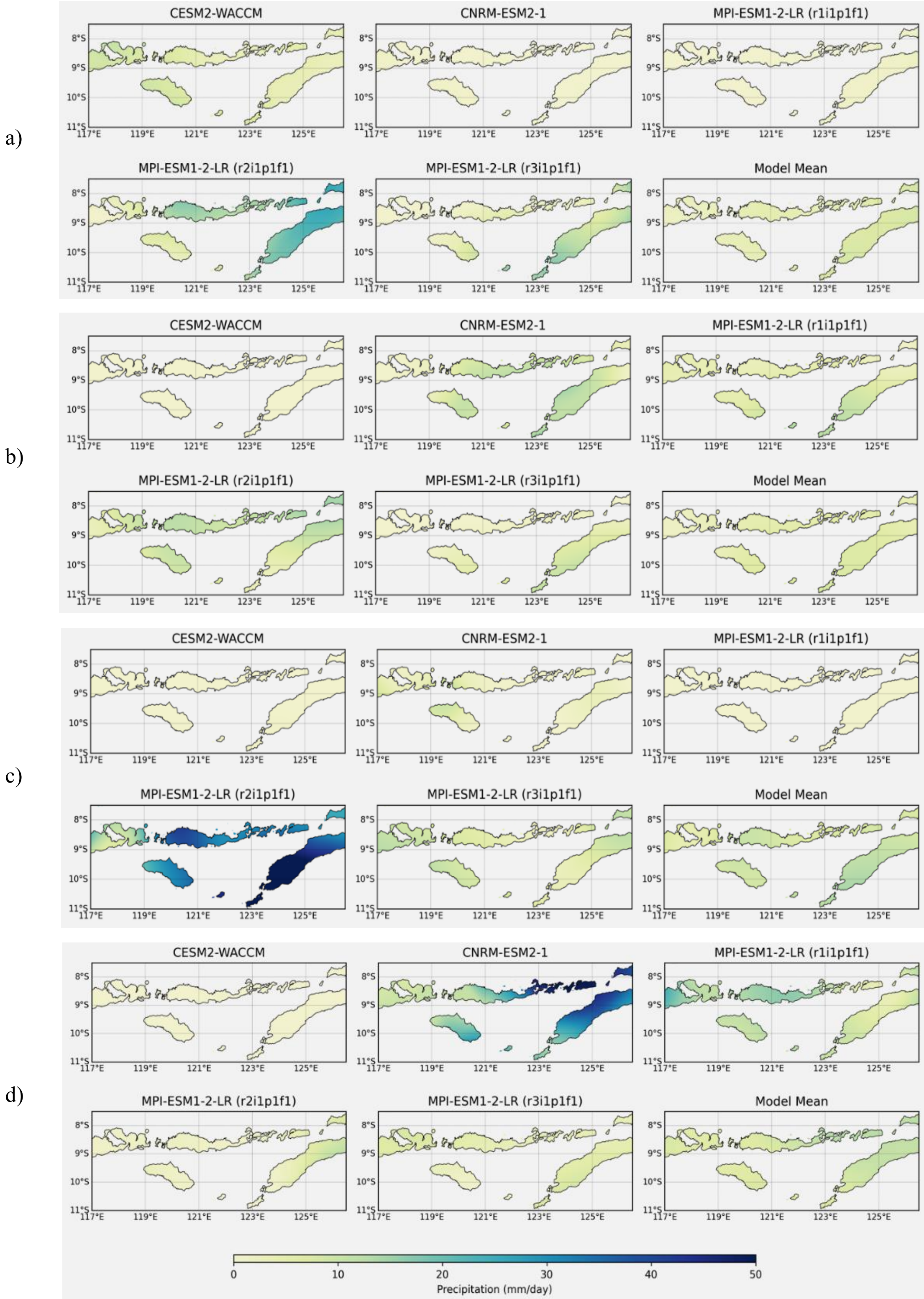


Fig. 4. The extreme rainfall (mm/day on April 03,2021) of Seroja TC from GeoMIP for the components of (a) G6solar, (b) G6sulfur, (c) SSP245 and (d) SSP585.

We compare the results of extreme rainfall data from ERA5 and the mean model of the five GeoMIP models. When TC Seroja passed, the extreme rainfall obtained from ERA5 data was 50 mm/day, but the extreme rainfall data from the mean model was around 10-20 mm/day. This shows that using GeoMIP decreases extreme rainfall from 50 mm/day to 10-20 mm/day.

4.2.3 ERA5 Data of Surigae TC

Surigae TC crossed eastern Indonesia on April 12-19, 2021, but the highest rainfall intensity occurred on April 16, 2021. We extracted data from ERA5 for Surigae TC on April 16, 2021, as shown in **figure 5**. The extreme rainfall intensity of Seroja TC is 50 mm/day in the southeast of Papua Island.

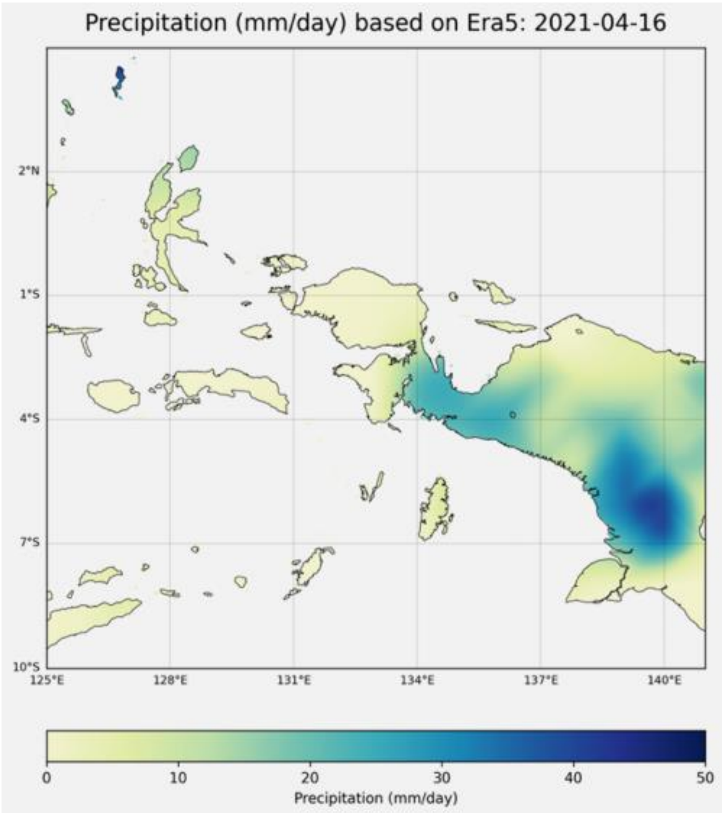
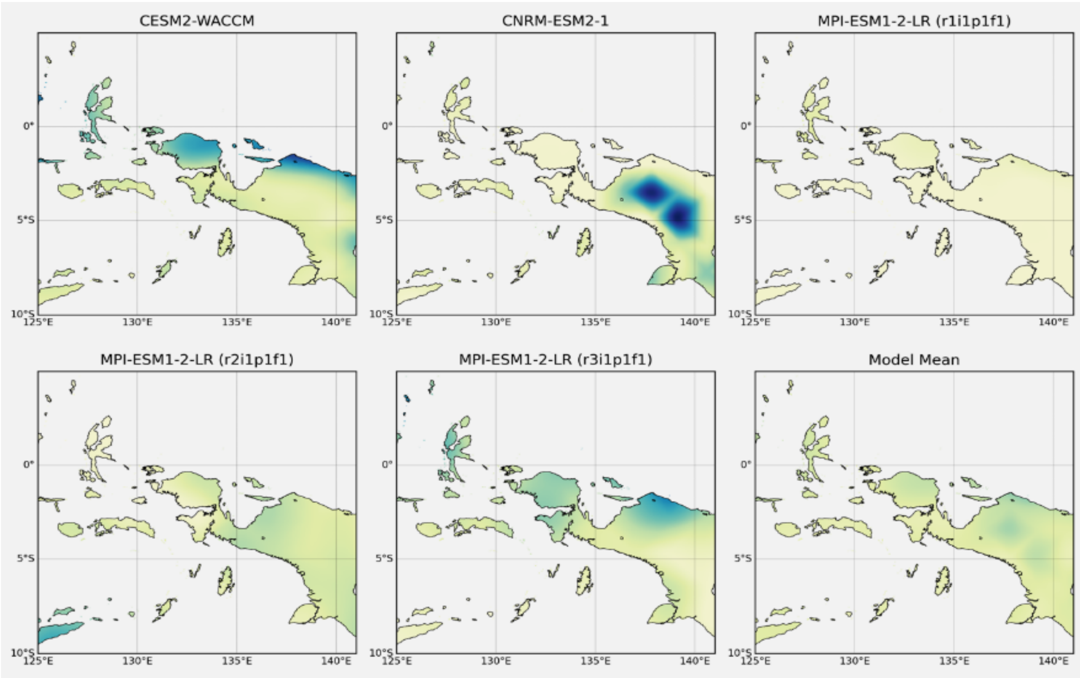


Fig. 5. The extreme rainfall of ERA5 data on 16 April, 2021 from Surigae TC.

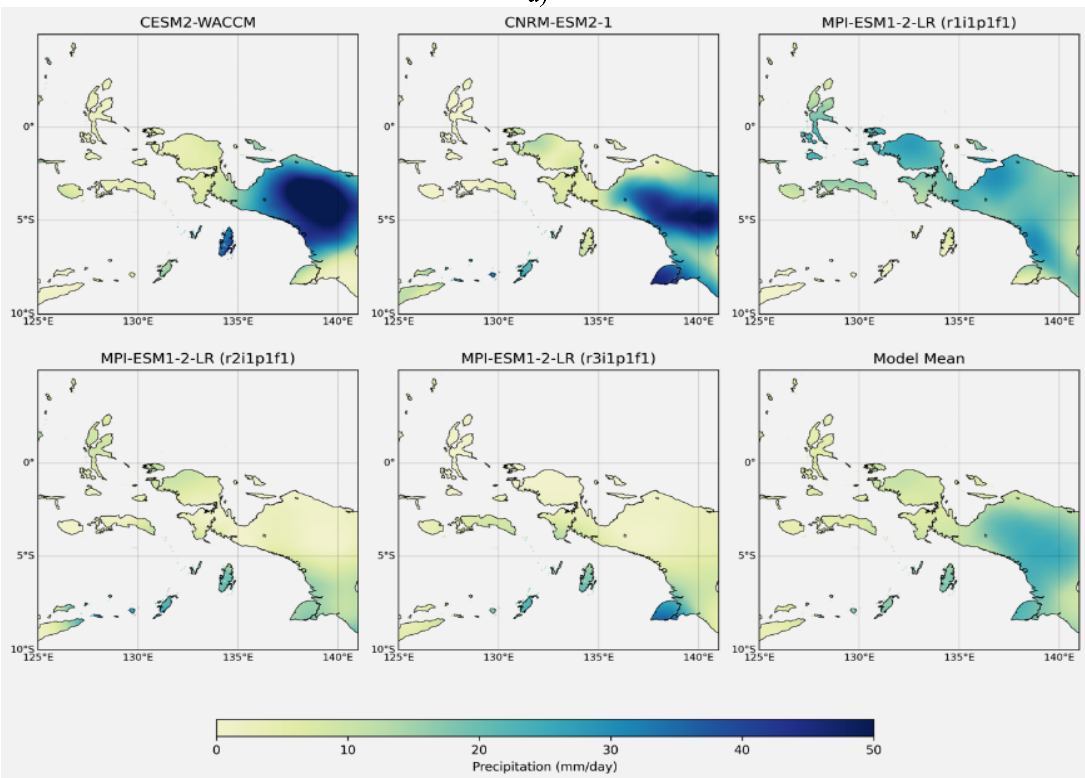
4.2.4. GeoMIP Data of Surigae TC

We also extracted data from GeoMIP on April 16, 2021, to compare with ERA5 data. The GeoMIP simulation model includes G6solar, G6sulfur, SSP245, and SSP585. In GeoMIP, five simulation models are used, as detailed in Table 1: CESM2-WACCM (1 model), CNRM-ESM2-1 (1 model), and MPI-ESM1-2-LR (3 models). Each model incorporates the four components—G6solar, G6sulfur, SSP245, and SSP585. We calculate the average across these five models and compare it with extreme rainfall data from Tropical Cyclone Surigae sourced from ERA5.

We compared the extreme rainfall data results between ERA5 and the mean output model from the five GeoMIP models (**Fig. 6**). During the passage of Tropical Cyclone Surigae, ERA5 recorded extreme rainfall at 40 mm/day, whereas the GeoMIP mean model showed values around 20-30 mm/day. This indicates that using GeoMIP reduces the extreme rainfall from 40 mm/day to 20-30 mm/day.

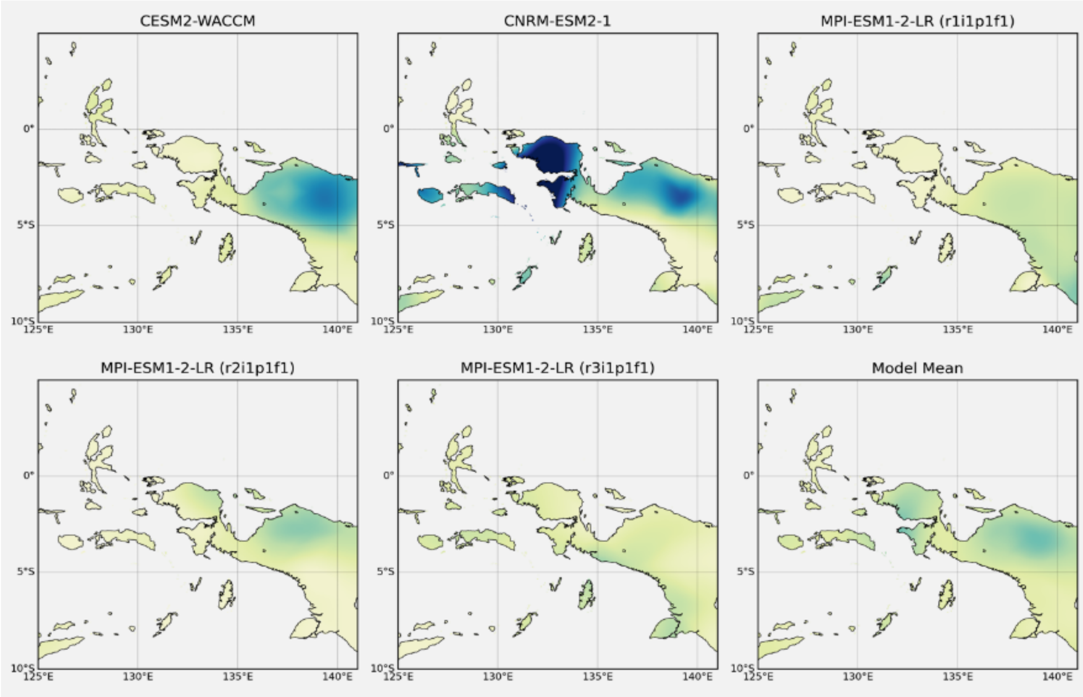


a)



b)

Fig. 6a and 6b. The extreme rainfall of Surigae TC from GeoMIP for the components of (a) G6solar and (b) G6sulfur.



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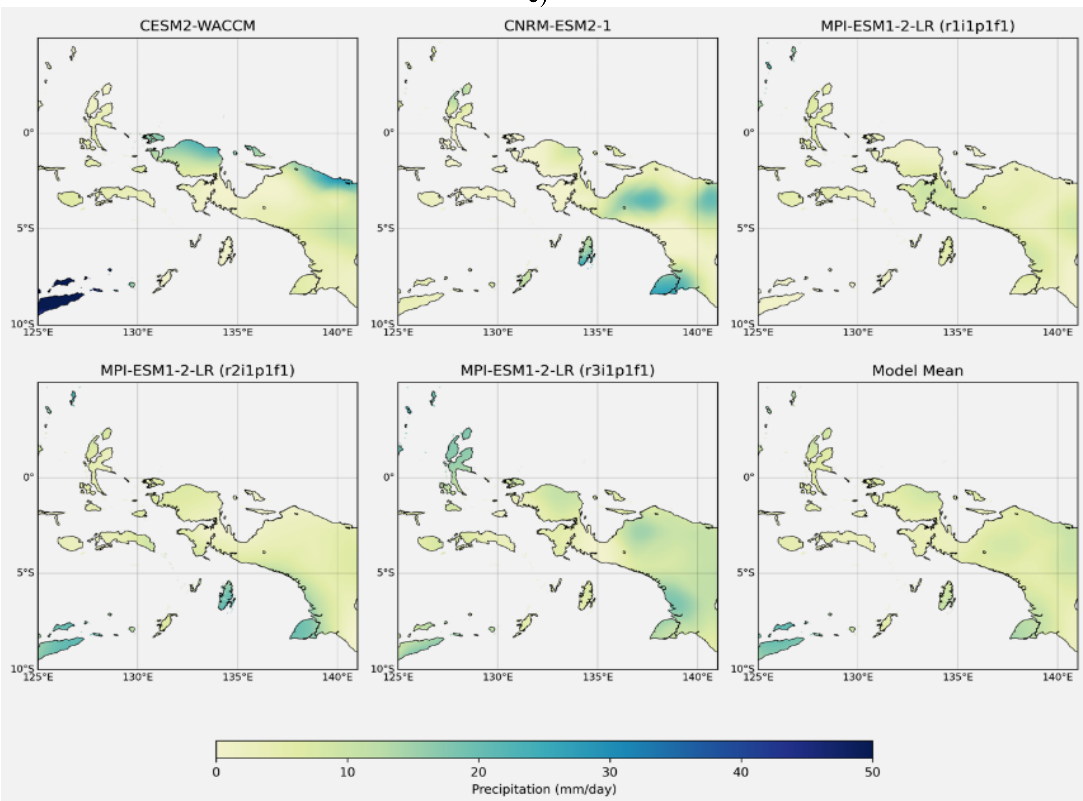


d)

Fig. 6c and 6d. The extreme rainfall of Surigae TC from GeoMIP for the components of (c) SSP245 and (d) SSP585.

4.2.5. ERA5 Data of Rai TC

Tropical Cyclone Rai passed through eastern Indonesia from December 13-20, 2021, with the peak rainfall intensity recorded on December 20, 2021. Data for Tropical Cyclone Rai on this date was extracted from ERA5, as illustrated in **figure 7**. The extreme rainfall intensity for Tropical Cyclone Rai reached 40 mm/day.

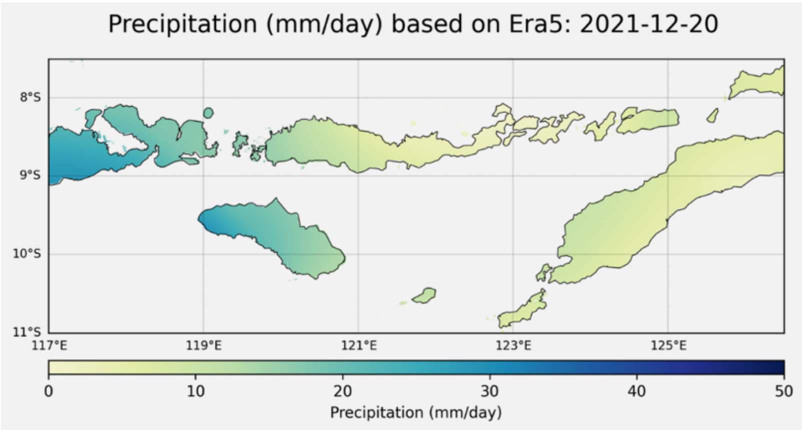


Fig 7. The extreme rainfall of ERA5 data on 20 December, 2021 from Rai TC

4.2.6. GeoMIP Data of Rai TC

Data from GeoMIP, extracted on December 20, 2021, was used to compare with ERA5 data. The GeoMIP simulation model consists of four components: G6solar, G6sulfur, SSP245, and SSP585. As outlined in Table 1, GeoMIP includes five simulation models: CESM2-WACCM (1 model), CNRM-ESM2-1 (1 model), and MPI-ESM1-2-LR (3 models). Each model includes the four components—G6solar, G6sulfur, SSP245, and SSP585 (**Fig. 8**). We averaged the results from these five models and compared them with extreme rainfall data associated with Tropical Cyclone Rai from ERA5.

The last result we compared Tropical Cyclone Rai with the peak of extreme rainfall on December 20, 2021. We obtained from ERA5 data that extreme rainfall on December 20, 2021, was 20-30 mm/day, while from the GeoMIP mean model, it was obtained around 20 mm/day. Like the previous 2 results, GeoMIP results also show a decrease in rainfall intensity. Table 2 summarizes the differences in extreme rainfall values between ERA5 and GeoMIP for each analyzed tropical cyclone:

Table 2.

Comparison of ERA5 and GeoMIP Extreme RainFall Data for Tropical Cyclones.

Tropical Cyclone (TC)	ERA5 Extreme Rainfall (mm/day)	GeoMIP Extreme Rainfall (mm/day)	Difference & Observations
Seroja (April 2021)	50	10-20	GeoMIP underestimated rainfall significantly compared to ERA5
Surigae (April 2021)	40	20-30	GeoMIP showed lower rainfall values, though closer to ERA5 compared to Seroja.
Rai (December 2021)	20-30	~20	GeoMIP results were more aligned with ERA5, indicating better model performance for this TC.

As shown in the table 2, GeoMIP tends to underestimate extreme rainfall, especially for Seroja TC, where the model output ranged between 10-20 mm/day, significantly lower than the 50 mm/day recorded by ERA5. However, this discrepancy is smaller for Rai TC, where GeoMIP's estimates are closer to the observed data.

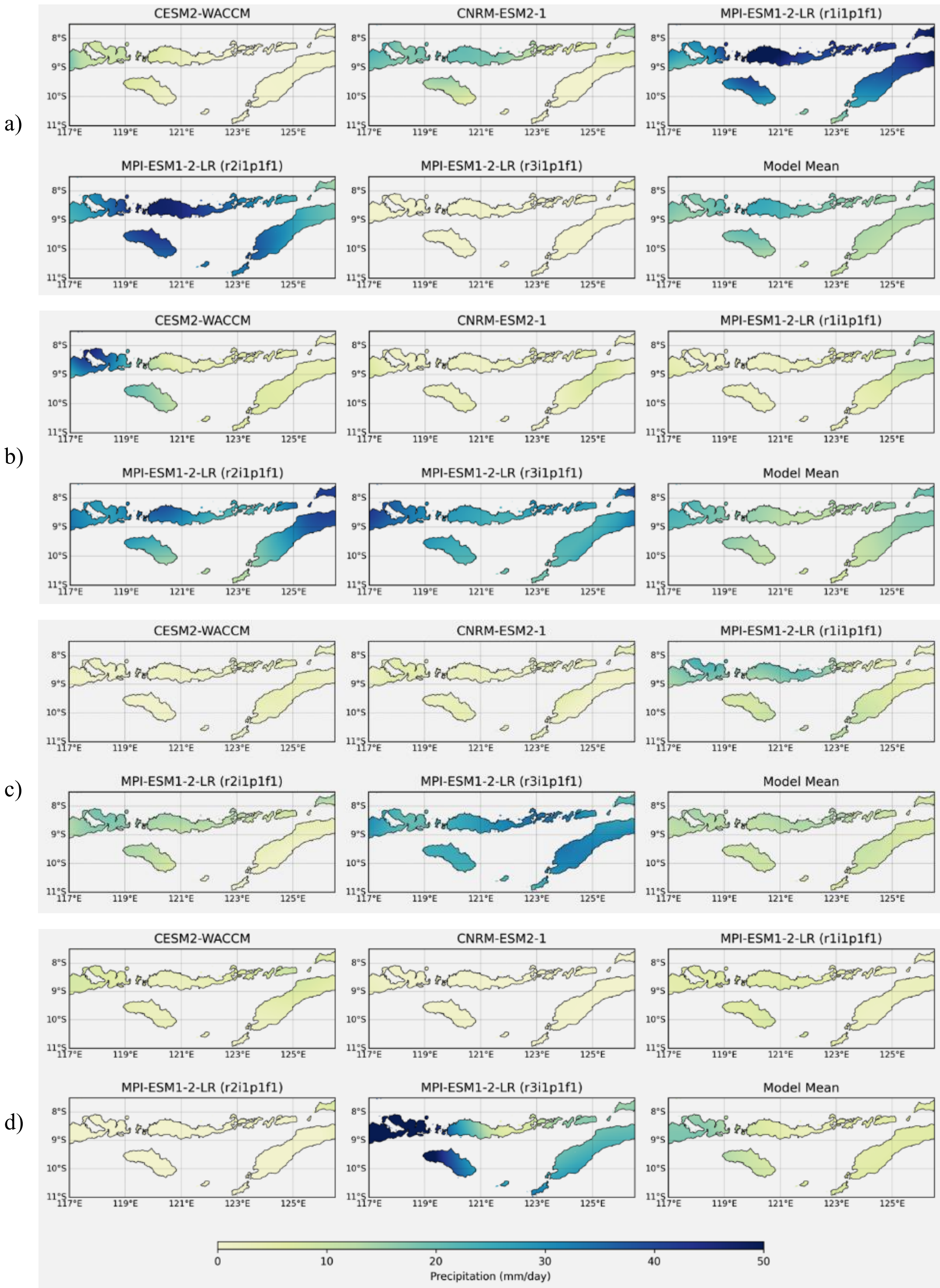


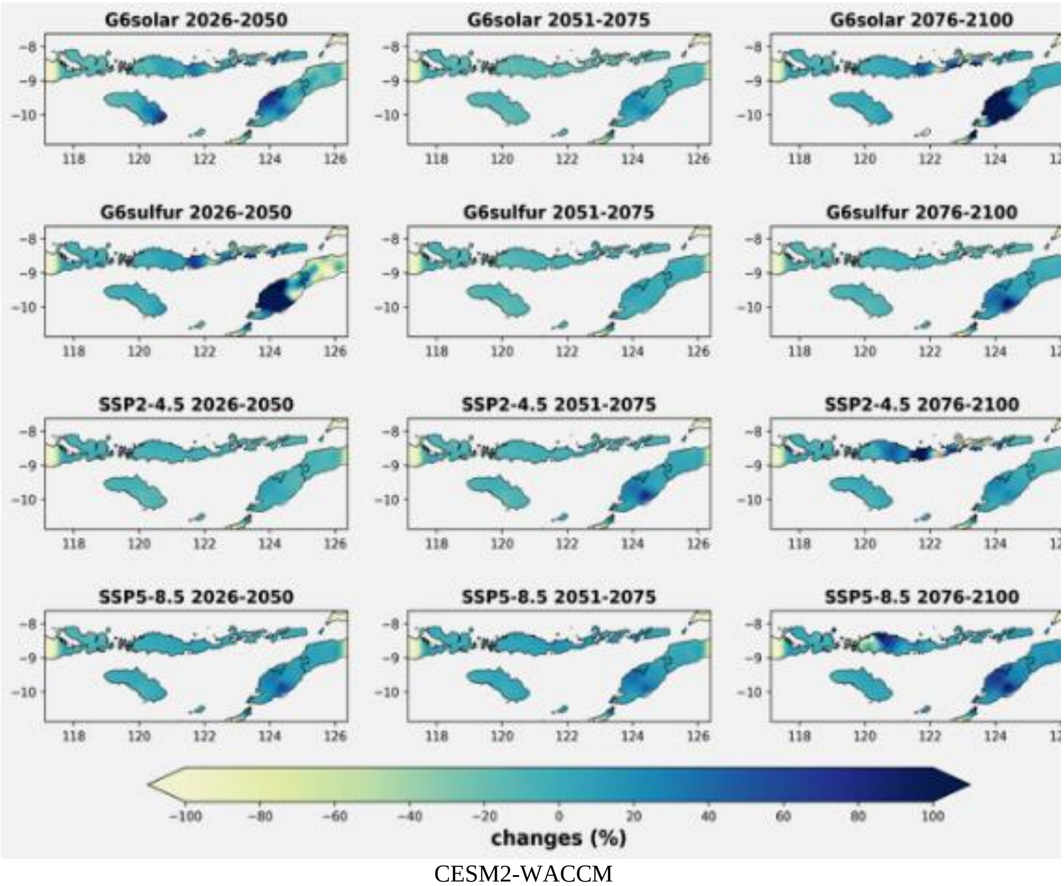
Fig. 8. The extreme rainfall of Rai TC from GeoMIP for the components of (a) G6solar, (b) G6sulfur, (c) SSP245 and (d) SSP585

The results indicate that SRM intervention effectively reduces extreme rainfall during tropical cyclones in eastern Indonesia, with notable decreases observed in TC Seroja, TC Surigae, and TC Rai. While this reduction may mitigate the risks of flooding and landslides, it also raises concerns about potential water shortages in affected regions. These findings highlight the need for integrated water resource management policies considering disaster risk reduction and long-term water availability.

Furthermore, the discrepancies between ERA5 and GeoMIP data suggest that model refinement is necessary to improve predictive accuracy. Potential biases in the GeoMIP approach, such as the simplification of cloud-aerosol interactions and the assumptions underlying the SRM mechanism, may contribute to underestimating precipitation. The spatial and temporal smoothing used in GeoMIP simulations may also smooth extreme precipitation events, resulting in lower projections of precipitation intensity. Future research should explore the optimization of SRM scenarios for localized climate conditions and assess their potential unintended consequences on atmospheric circulation, biodiversity, and agricultural productivity. Additionally, given the projected increase in extreme rainfall under high-emission scenarios (SSP5-8.5), further investigation into adaptive strategies, such as sustainable land-use planning and resilient infrastructure development, is essential to enhance climate resilience in cyclone-prone regions.

4.3. Future Changes Analysis of Extreme Rainfall

First, we assess the future projection of extreme precipitation over the East Nusa Tenggara (**Fig. 9**) and Papua regions (**Fig. 10**) in 2026-2050, 2051-2075, and 2076-2100.

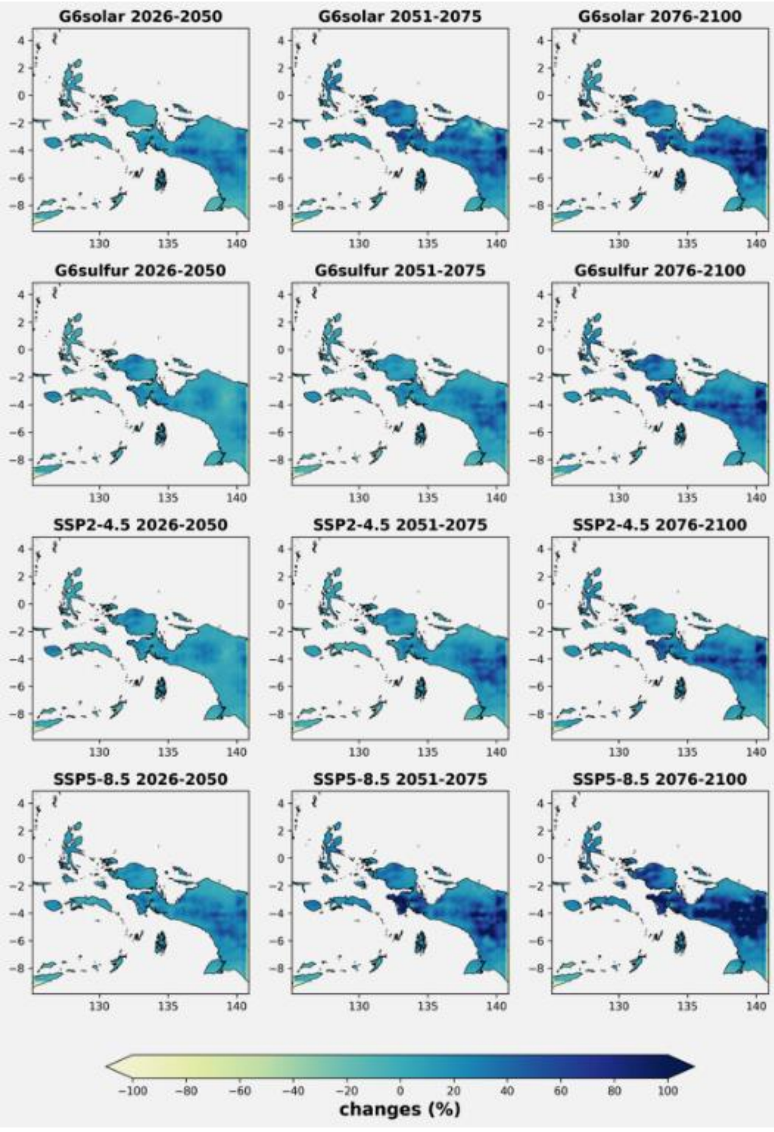


CESM2-WACCM

Fig. 9. Future change of the precipitation in East Nusa Tenggara Province.

The changes are calculated for these periods relative to the baseline period (1990-2014) under Scenario Model Intercomparison Project (ScenarioMIP) output SSP2-4.5 and SSP-5.85 (ScenarioMIP - Baseline). We also evaluated changes in the Geoengineering Model Intercomparison Project (GeoMIP) output using the G6Solar and G6Sulfur experiments (GeoMIP - Baseline). In addition, we calculated the anomaly SRM in the future by determining the changes in GeoMIP output relative to SSP-2.45 as the reference scenario (GeoMIP - SSP2-4.5). This allows us to assess the projected changes in the characteristics of precipitation extremes in the future with radiation modification geoengineering strategies (Eyring et al., 2016).

The East Nusa Tenggara province shows changes in the precipitation index over the Kupang regency in the future relative to the conditions of 1990-2014. Based on spatial distribution, both SSP scenarios indicate more significant change than the geoengineering modification for most East Nusa Tenggara province regions.



CNRM-ESM2-1

Fig 10. Future change of the precipitation in Papua Province (The other four models can be found in the supplement file)

The highest percentage change of Rx1day is shown under the SSP5-8.5 scenario with an increase of 10% to 60% from the baseline condition, especially at the end of the 21st century (2076-2100). In addition, SRM under the G6Solar and G6Sulfur experiments displayed 5% to 20% changes over most of the East Nusa Tenggara Province. On the other hand, SRM projected a slight decrease in the Rx1day index to 50% from the baseline in the West and East parts of Nusa Tenggara Province.

In Papua province, precipitation index changes are projected for the Merauke regency (lower right in **figure 8**) in future scenarios compared to conditions from 1990-2014. Spatial distribution analysis shows that both SSP scenarios indicate a greater change than geoengineering modifications across most regions of Papua province. Same as in the East Nusa Tenggara province, the SSP5-8.5 scenario presents the largest increase in the Rx1day index, ranging from 30% to 70% above baseline conditions, for a period of 2076-2100.

SRM experiments under the G6Solar and G6Sulfur scenarios show 10% to 20% changes across most areas of Papua. Conversely, SRM projects a slight reduction in the Rx1day index, up to 60% below baseline, located in the eastern part of Papua province (see on the right side of the CESM2-WACCM model).

5. CONCLUSIONS

Based on the results of the above analysis, SRM intervention can reduce extreme rainfall in TC Seroja from 50 mm/day to 10-20 mm/day, in TC Surigae from 40 mm/day to 20-30 mm/day and in TC Rai from 20-30 mm/day to 20 mm/day. Projections for East Nusa Tenggara indicate an increase in Rx1day rainfall by 10% to 60% under the SSP5-85 scenario. While in the province of Papua, specify an increase for Rx1day rainfall by 30% to 70%. SRM under the G6Solar and G6Sulfur experiments showed changes of 5% to 20% in East Nusa Tenggara province and 10% to 20% changes in Papua province.

The implications of reduced rainfall due to SRM need to be futher examined in the context of disaster mitigation. While the decrease in extreme rainfall may help reduce the risk of flooding and landslides, there are also potensial risks, such as reduced water availability for communities and ecosystems. Therefore, further research is needed to improve model accuracy and understand the long-term effects of SRM on climate patterns and other extreme weather events.

ACKNOWLEDGEMENTS

This work was funded by the Degrees Modeling Fund (DMF) from the Degrees Initiative.

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