Assessing Future Seasonal Rainfall in Bintan Island using CORDEX-SEA Data

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ABSTRACT. *Bintan Island (1.173 km^2) faces water resources constrains due to its small catchment area and low geological water retention. The high dependence of water resorces on rainfall makes them highly susceptible to climate change. Rising water demand due to population growth and economic development further intensifies the risk of water scarcity. Therefore, integrating climate change consideration into water resources planing is essential to ensure long-term water security. The main limitation in assesing future rainfall is the lack of high-resolution climate data model projection. The study aims to provide higher spatial resolution future rainfall by downscaling CORDEX-SEA projection model data under RCP 4.5 scenario for 2006 – 2045 period. Statistical downscaling using the quantile mapping method was applied to enhance spatial resolution and correct biases between the climate model outputs and observed data. Model outputs of correction results show a better conformity with observed rainfall data, improving the realibility of the projections. Probability analysis indicates a decrease in future seasonal rainfall across the island, particulary during JJA (Juni-August). About 80% of the area is projected to experience below normal rainfall with probabilities ranging from 40% to 65%. The northern part of Bintan may experience a rainfall increase during the SON (September-November). The eastern part of the Island was identified as a suitable location for water reservoir development, as it's projected to experience reduced rainfall only during DJF (December-February). Developing reservoirs in this area could support future water security in response to projected rainfall decrease and enhance the island's resilience to climate change.*

Keywords: Future-rainfall, probability, CORDEX_SEA, Climate-change

1 INTRODUCTION

Climate change is believed to be currently occurring and is expected to significantly affect rainfall patterns in Indonesia, leading to shifts in seasonal timing, changes in the duration of the rainy season, and an increase in the frequency of extreme rainfall events (Qalbi et al. 2016; Kurniadi et al. 2024). As the world's largest archipelagic nation, Indonesia faces substantial challenges in adapting to climate change. Small islands, in particular, are highly vulnerable due to their limited natural resources, high exposure to climate-related hazards, and low adaptive capacity (Nagu, Lessy, and Achmad 2018; Suroso et al. 2009; Zulriskan, Hasibuan, and Koestoer 2018).

Bintan Island, located in western Indonesia, is a small island with limited water resources. Its geological structure is dominated by very low-porosity granite rocks, resulting in a low groundwater storage capacity. Consequently, the availability of water resources is highly dependent on rainfall, making them highly sensitive to climate changes. Bintan is particularly susceptible to hydroclimatic variability and climate change impacts. As with many small islands, these conditions elevate the region's hydrological vulnerability, underscoring its status as a critical zone for water resource sustainability and climate resilience. Bintan Island covers only about 1,173 km², it has experienced significant development due to its strategic geographical location (Narulita et al., 2021). As the largest island in the Riau Archipelago, Bintan has gained increasing administrative and economic significance in recent years. In 2002, following the implementation of Republic of Indonesia Law No. 25 of 2002, the provincial capital of the Riau Islands Province was relocated from Batam to Bintan, in part to support the spatial and environmental restoration effort in the more densely populated Batam Island. Later, under the Republic of Indonesia Law No. 41 of 2017, Bintan was designated as part of the newly established Free Trade Zone (FTZ), aimed at stimulating regional economic growth. These developments have significantly increased the demand for raw water, particularly in the industrial and service sectors, driven by rapid expansion in key FTZ areas such as Galang Batang, the Maritime Industrial Zone, Lobam Island (Bintan Regency), and the Senggarang and Dompak Darat Industrial Zones (Tanjung Pinang City). These policy changes have positioned Bintan as a development key zone, by expecting a significant increase of the population economic activity on the island.This progress will place additional pressure on the island's already limited water resources, underscoring the urgent need for sustainable and climate-resilient water management strategies.

Several previous studies have shown that regional ocean–atmosphere interactions, such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), play a significant role in driving rainfall anomalies across Indonesia (Behera et al., 2008; Trenberth et al., 2002; Chang et al., 2016; Kurita et al., 2018). In addition to ENSO and IOD, other atmospheric phenomena such as the Madden–Julian Oscillation (MJO) and broader synoptic-scale dynamics further contribute to the rainfall variability in the region. Bintan Island, located in the western part of the Indonesian maritime continent, exhibits a complex rainfall pattern influenced by these large-scale climate drivers. The Intertropical Convergence Zone (ITCZ), in particular, is associated with the island's bimodal rainfall peaks occurring in April–May and October–November (Aldrian and Dwi Susanto 2003; Narulita et al. 2021). Narulita et al. (2023) also emphasized the role of synoptic atmospheric dynamics in modulating rainfall over Bintan Island.

Given the strong influence of these interacting climate systems, predicting future seasonal rainfall in the region remains a significant challenge. This complexity is of particular concern for Bintan Island, where water resources are highly dependent on rainfall.

Consequently, assessing future rainfall projections is essential for effective water resource management and climate adaptation planning.

Since Bintan Island's water resources are closely tied to rainfall, projecting future rainfall patterns is crucial for effective water resource management (Narulita et al., 2021). The above facts show that the careful estimation of future rainfall is critical for sustainable water resource planning on Bintan Island, particularly in the context of the climate change mitigation. The Southeast Asia Regional Climate Downscaling (SEACLID) Project has produced the Coordinated Regional Downscaling Experiment for Southeast Asia (CORDEX-SEA), which is the high-resolution climate projection data currently available. High-resolution regional climate models, such as those from CORDEX-SEA, provide valuable projections of future seasonal rainfall. However, their native spatial resolution (25 km × 25 km) remains inadequate for capturing localized climate variability on small islands. Consequently, statistical downscaling and bias correction are necessary to refine these projections and enhance their applicability at the local scale.

To address the necessity, the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) product provides an effective reference dataset for spatial enhancement. The CHIRPS dataset, developed by the Famine Early Warning Systems Network (FEWS NET: USGS, NOAA, USDA, USAID, Chemonics, and Kimetrica), integrates satellite-based infrared precipitation estimates with ground-based station observations, delivering daily rainfall data at a high spatial resolution of approximately 0.05° (~5 km). CHIRPS serves as the baseline reference for spatial data resolution improvement in this study. Although CHIRPS is subject to certain limitations, particularly in capturing localized extreme events and daily variability, it offers robust spatial detail and a long-term temporal record, rendering it suitable for climate studies in data-sparse and geographically constrained areas such as Bintan Island (Ahana et al. 2024; Al-Shamayleh et al. 2024)). By employing CHIRPS as the observational benchmark, bias correction and spatial downscaling of CORDEX-SEA outputs were conducted, resulting in enhanced spatial resolution (5 km × 5 km) and a significant reduction in systematic bias. The improved datasets are expected to be more representative of local precipitation dynamics and are therefore more suitable for hydrological assessments and climate impact studies. The reliability of CHIRPS for such applications in Bintan Island has been corroborated by previous studies (Auliyani & Wahyuningrum, 2021; Narulita et al., 2021; Wahyuni, Sisinggih, & Dewi, 2021), particularly in regions lacking dense observational networks.

The purpose of this study is to answer the challenge of providing a prognosis of future rainfall on Bintan Island in order to support the preparation of sustainable water resources management planning.

2 MATERIALS AND METHODOLOGY

2.1 Location and Data

Study area

Bintan Island (Fig. 1) is situated between latitudes 0°49′ and 1°15.1′ N and longitudes 104°13.3′ and 104°41.3′ E. The island's location nearby the entrance to the South China Sea, the Karimata Strait, and the Malacca Strait is strategic.

The area of Bintan Island is about 1,173 km2. The island has the second largest population in Riau Island, behind Batam Island. There are about 411.420 people living on Bintan Island. Its growth rate, at about 1.3%, is higher than Indonesia's average growth rate of 1.11% (BPS Kota Tanjungpinang 2025; BPS Kabupaten Bintan 2025). Water demand increases according to the growth of the population and their economic activity, which is predicted to still arise in the future.

Based on the geological map by Kusnama (1994), Bintan Island is predominantly composed of claystone, shale, clay sandstone, quartz sandstone, and conglomerate, covering approximately 80% of its area. These sedimentary rocks exhibit low to moderate permeability, as confirmed by field observations, and have a limited capacity for groundwater storage.

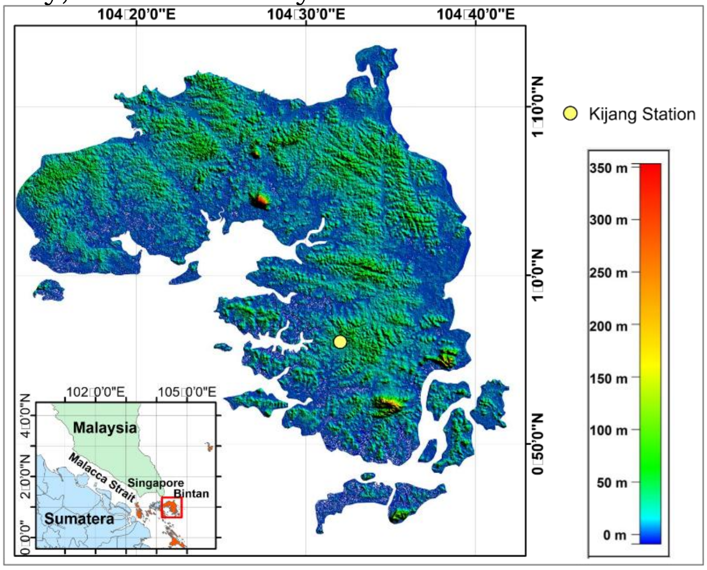


Figure 1. Research Location, Bintan Island

2.2 Standardization of data

The observation data used in this study include the ground observations from the Kijang station (1981-2021) and corrected CHIRPS daily rainfall (Narulita et al. 2021) for the historical period (1981–2005) and the actual period (2006–2021). For the projection data, we used outputs from CORDEX-SEA regional climate models under the RCP 4.5 scenario for the 2006 – 2045 periods. Four models were selected: the Center National de Recherches Météorologiques (CNRM), the European Community Earth-System Model (EC-Earth), the Max Planck Institute Earth System Model (MPI), and the Commonwealth Scientific and Industrial Research Organization (CSIRO), comprise both the historical (1981–2005) and future (2006–2045) periods. These projection models are available from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) and are offered at daily temporal resolution and spatial resolution of 25 km, covering Southeast Asia domain (SEA: 89.5° E-146.5° E, 14.8° S-27.0° N)

2.3 Methods

Bias Correction

We perform the bias corections using statistical quantile mapping method (Inomata, et al., 2011). Bias correction was performed through a multi-stage process. First, the CHIRPS data (1981–2021) were bias corrected to the ground observations of the Kijang station (1981-2021). The resulting correction factors were then applied to all CHIRPS grid points over Bintan Island. Next, CORDEX-SEA historical data (1981–2005) were corrected to the corrected CHIRPS dataset (1981-2005) as a reference (Narulita, Fajary, Syahputra, et al. 2021). Finally, these correction factors obtained from the second corrections were applied to the CORDEX-SEA future projections (2006–2045).

The first step in this method is to rank the CHIRPS daily rainfall series and CORDEX-SEA, and samples with NEP>= 95% were extracted from both datasets. The correction factors for each quantile (a_n, n=0, 0.1, ..., 1) from cumulative distribution function (CDF) rank were obtained from two rainfall time series sourced from the corrected CHIRPS and CORDEX-SEA on the grid point closest to the CHIRPS grid point. Then the correction factors were applied to the nearest grid point of CORDEX-SEA over Bintan Island. Mathematically the correction factor is written

$$\alpha_q = \frac{R_{REFERENCE_q}}{R_{UNCORRECTED_q}} \quad (1)$$

Where:

α_q = correction factor for the q^th quantile.
$R_{REFERENCE_q}$ = reference rainfall value (either ground-based measusrement or corrected CHIRPS) at the q^th quantile.
$R_{UNCORRECTED_q}$= rainfall value to be corrected (either CHIRPS or CORDEX-SEA) at the q^th quantile.

The calculation of correction factors distinguishes between extreme and non-extreme daily rainfall values. Extreme values are defined as the upper 5% of the rainfall distribution based on non exceedance probability (NEP). The modification from the conventional bias correction method (Inomata et al., 2011) involves the exclusion of zero rainfall values from the cumulative distribution function (CDF) and the use of a non-exceedance probability (NEP) threshold of ≥95% (Anagnostopoulou and Tolika 2012), instead of >99.5% threshold used in previous study (Inomata et al., 2011; 2012). This modification was made because zero precipitation creates a long, flat segment in the CDF, which does not meaningfully contribute to the bias correction. Using NEP >99.5% captures only a small few extreme outliers, whereas NEP ≥95% NEP threshold, provides a more robust and representative way for correcting extreme rainfall values across the time series. Next, the correction factor of extreme value is calculated for each quantile on this data segment. For non-extreme values, data are separated monthly and ranked. We exclude zero values in the calculation. The correction factor is the ratio of the non-extreme monthly quantile value of field observations (corrected CHIRPS) to that of CORDEX-SEA rainfall model, calculated every month. The derived correction factors are applied to the CORDEX-SEA rainfall data by applying each correction factor value to its corresponding quantile and adjusting it, resulting in corrected CORDEX-SEA rainfall data. For extreme values, the equation is as follows:

$$R\_CORDEXSEA\_COR_q = \alpha_{q\_m} \times R\_CORDEXSEA_q \qquad \text{......................... (2)}$$

$$R\_CORDEXSEA\_COR_{q\_m} = \alpha_{q\_m} \times R\_CORDEXSEA_{q\_m} \qquad \text{.................. (3)}$$

With:
R_CORDEXSEA_COR_q is CORDEX-SEA rainfall corrected on a quantile-q. R_CORDEXSEA_COR_nm id CORDEX- SEA rainfall corrected on a quantile-q and month-m (m=1, 2...12).

Table 1. Overview of Representatif Concentration Pathways (RCPs) (van Vuuren et al. 2011)

	Description
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100
RCP 6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO2 eq) at stabilization after 2100
RCP 2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100)

This study uses climate change scenarios that refer to the Representative

Concentration Pathways (RCPs) scenario (van Vuuren et al., 2011) adopted by IPCC AR5 (IPCC, 2007). The list of scenarios is as table 1.

Normal seasonal rainfall calculation

Normal monthly rainfall was calculated as the average of monthly precipitation over the baseline period. In this study, CHIRPS data from 1981 to 2005 were used to generate the normal monthly rainfall. The normal CHIRPS monthly rainfall was subsequently compared with projections from the CORDEX-SEA climate models.

Probability of future rainfall calculation

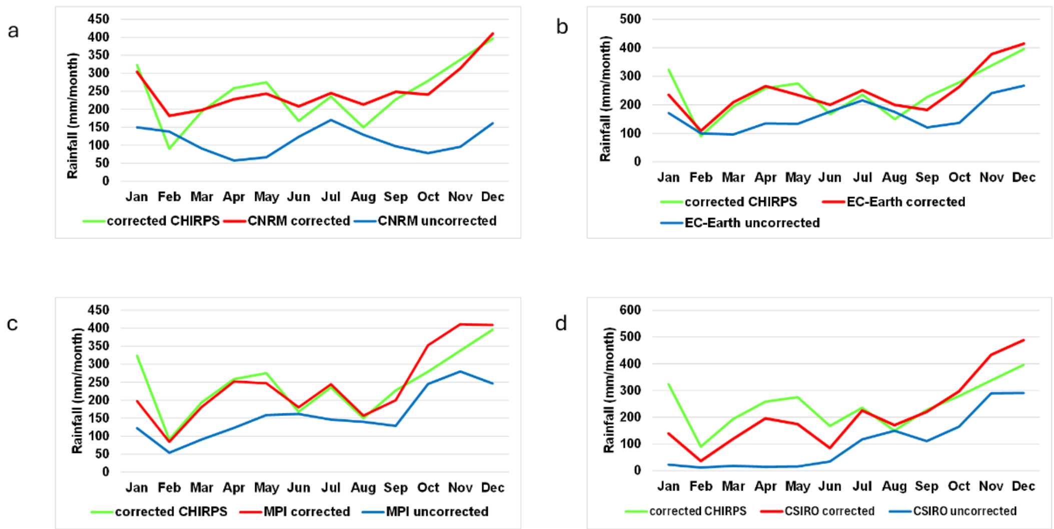
Future rainfall probabilities were predicting based on four CORDEX-SEA models: CNRM, CSIRO, EC-Earth, and MPI. The normal monthly rainfall data served as the baseline for assessing future seasonal rainfall projections. The difference between the bias-corrected projected rainfall values (CORDEX-SEA) and the normal rainfall values (CHIRPS) was calculated to evaluate future changes. "Above normal" rainfall is defined as rainfall exceeding 15% of the normal value, while "below normal" rainfall is defined as rainfall falling below 15% of the normal value. The probability of future rainfall was determined by dividing the number of future rainfall events by the total number of events, expressed as a percentage probability.

3 RESULTS AND DISCUSSION

RESULT

Bias Correction Method for improving climate model quality

Figure 2 presents the bias-corrected CORDEX-SEA dataset for the historical period (1981–2005), demonstrating the effectiveness of the correction in reducing deviations from observed rainfall patterns.



e.

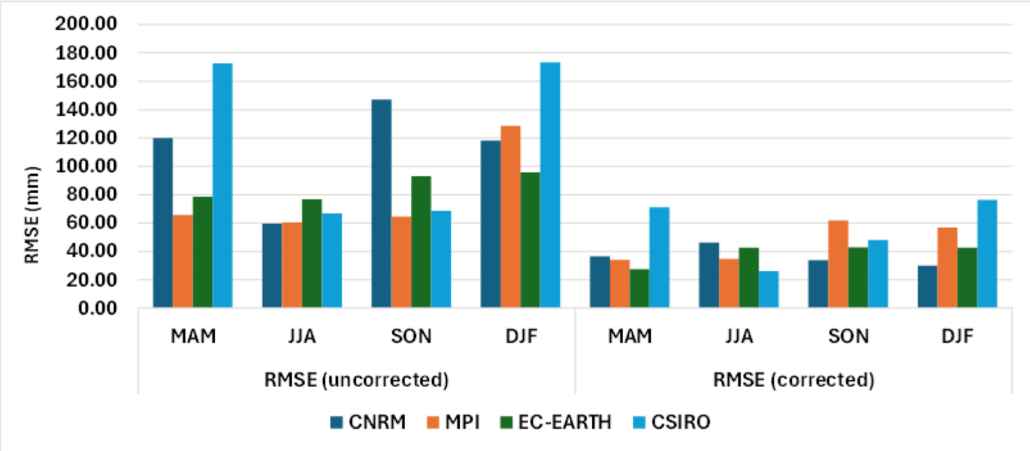


Fig 2 (a-d). Monthly climatology of rainfall over Kijang station grid point from corrected CHIRPS as observation data (greenline), uncorrected CORDEX-SEA (blue line), and corrected CORDEX-SEA (red line) at baseline period. Figure 2 (e). The Root Mean Square Error (RMSE) between uncorrected and corrected CORDEX-SEA at baseline period.

Figures 2a–2d illustrate the monthly rainfall climatology at the Kijang station grid point, showing that the bias-corrected CORDEX-SEA data aligns more closely with observations compared to the uncorrected data. These results confirm that the bias correction method applied in this study effectively minimizes discrepancies between CORDEX-SEA projections and the corrected CHIRPS observational dataset. As shown in Figure 2e, the Root Mean Square Error (RMSE) between CORDEX-SEA outputs and CHIRPS observations decreases substantially after bias correction, indicating enhanced model performance and a more accurate representation of observed rainfall patterns.

Seasonal Rainfall of Bintan Island based on corrected CHIRPS data

Figure 3 illustrates the seasonal distribution of rainfall on Bintan Island during the MAM (March–May), JJA (June–August), and SON (September–November) periods. The data show that the primary rainy season occurs during the DJF (December–February) season, with an average rainfall of 281 mm. The dry season is observed during the JJA season, with a lower average rainfall of approximately 153 mm. The transition from the dry season to the rainy season occurs during the SON period, as indicated by an increase in average rainfall to 240 mm compared with the JJA season. Notably, in the western region of Bintan Island during SON, rainfall remains relatively low at around 175 mm. Conversely, the transition from the rainy season to the dry season occurs during the MAM period, with an average rainfall of 188 mm. Within MAM, the western part of the island experiences lower rainfall (approximately 150 mm), while the southern part records higher rainfall, around 225 mm.

Furthermore, Figure 3 shows a bimodal rainfall distribution pattern across Bintan Island, with notable rainfall maxima in the northern and southern regions (Narulita et al., 2021). During the DJF season, rainfall is generally well distributed across the island; however, the northwestern region receives slightly less rainfall than the southern areas.

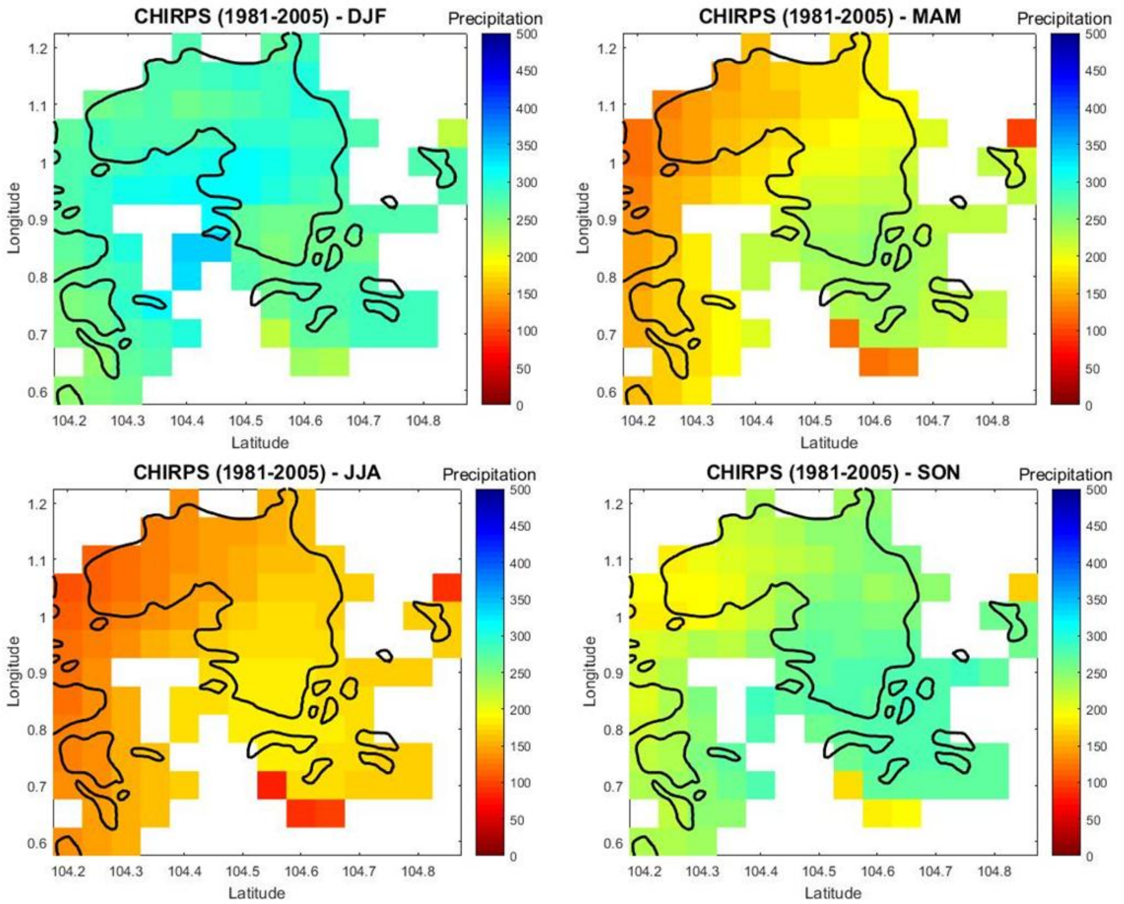


Figure 3. The seasonal Rainfall of Bintan Island based on corrected CHIRPS at historical periode (1981-2005)

Rainfall Projection Based on Corrected CORDEX-SEA Data for Bintan Island

To validate the bias correction applied to the CORDEX-SEA climate models, it is essential to first examine monthly climatology patterns during the baseline period (1981–2005). The validation was then performed for the period 2006–2021. The results show that bias correction effectively aligns the model outputs with the observed climatological data. The outcomes for the period 2006–2021 are detailed at Figure 4. Below:

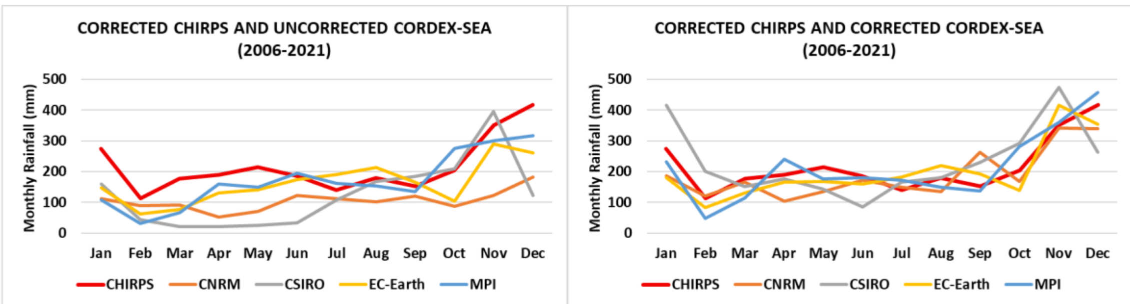
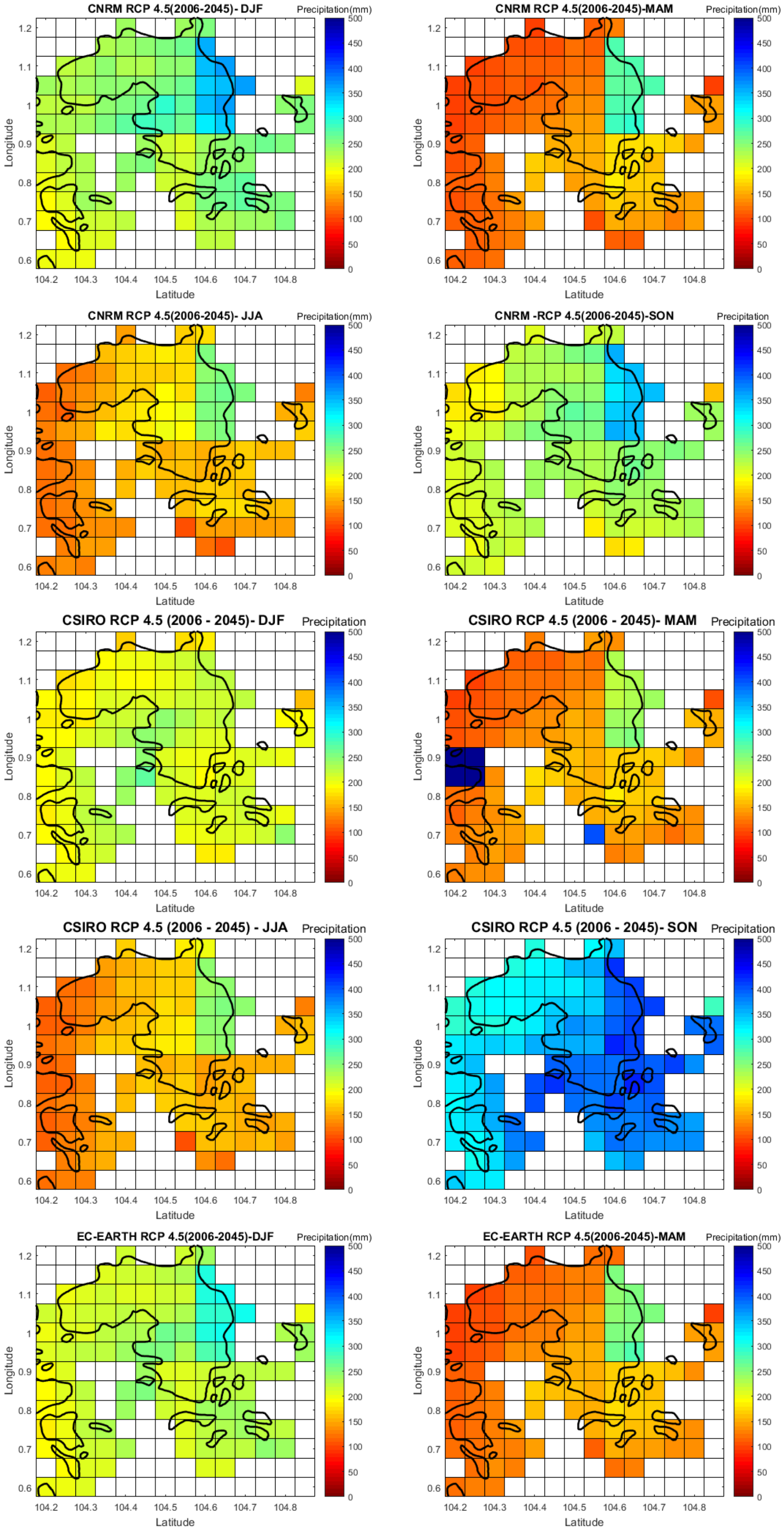


Figure 4. Evaluation of Corrected and Uncorrected CORDEX-SEA Rainfall Data (CNRM, CSIRO, EC-Earth and MPI). versus Corrected CHIRPS(Observations)


CNRM RCP 4.5(2006-2045)- DJF
CNRM RCP 4.5(2006-2045)-MAM
CNRM RCP 4.5(2006-2045)- JJA
CNRM -RCP 4.5(2006-2045)-SON
CSIRO RCP 4.5 (2006 - 2045)- DJF
CSIRO RCP 4.5 (2006 - 2045)- MAM
CSIRO RCP 4.5 (2006 - 2045) - JJA
CSIRO RCP 4.5 (2006 - 2045)- SON
EC-EARTH RCP 4.5(2006-2045)-DJF
EC-EARTH RCP 4.5(2006-2045)-MAM
Precipitation(mm)
Precipitation
Longitude
Latitude
1.2
1.1
1
0.9
0.8
0.7
0.6
104.2
104.3
104.4
104.5
104.6
104.7
104.8
500
450
400
350
300
250
200
150
100
50
0

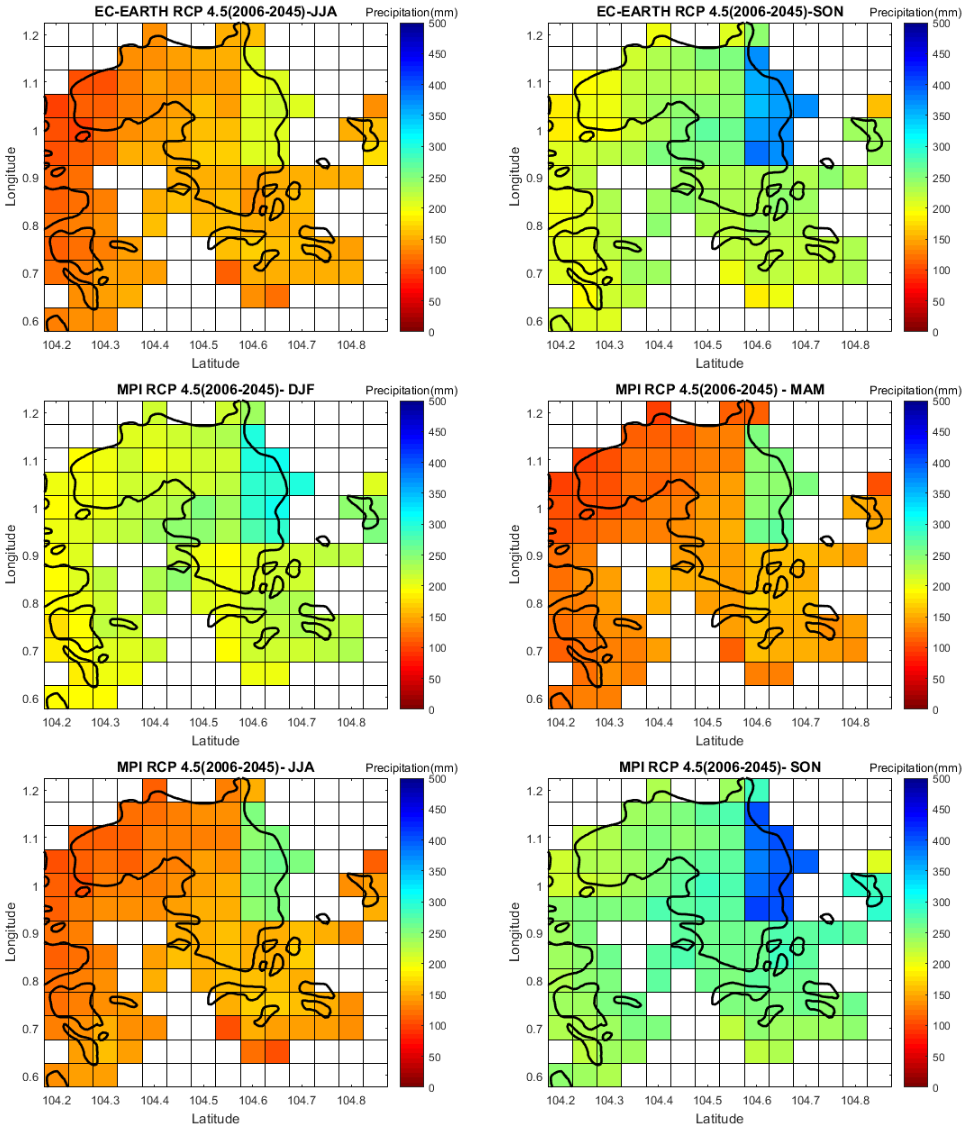


Figure 5. Future Seasonal Rainfal of corrected CORDEX-SEA data (CNRM, CSIRO, EC-Earth and MPI)

Table 2. Maximum, Minimum and average of the seasonal rainfall projection (mm) based on corrected CORDEX-SEA Climate model (CNRM, CSIRO, EC-Earth and MPI) under RCP 4.5 for 2006 – 2045 period.

Rainfall (2006 -2045)	Rainfall (mm)	MAM	JJA	SON	DJF
CNRM	Maximum	293.267	263.273	358.235	362.036
	Minimum	95.295	104.791	157.321	191.065
	Average	145.724	163.835	237.669	249.548
CSIRO	Maximum	400.748	256.063	422.088	270.969
	Minimum	100.430	103.587	288.054	161.544
	Average	153.445	158.730	358.409	207.691
EC-EARTH	Maximum	275.573	218.485	383.532	307.037
	Minimum	93.931	98.553	160.623	180.343
	Average	146.950	147.808	238.966	227.168
MPI	Maximum	253.511	258.140	370.143	299.050
	Minimum	93.607	94.038	173.992	159.631
	Average	136.752	138.578	226.487	199.875

Figure 5. and Table 2. shows the seasonal rainfall projections using the corrected CORDEX-SEA with CNRM, CSIRO, EC-Earth, and MPI models in a 5-kilometer spatial resolution. According to the models, the DJF and SON seasons receive an average of more than 200 mm of rainfall, while the MAM and JJA seasons frequently receive less than 100 mm on average. Generally, the wet season occurs in the DJF and SON seasons, and the dry season occurs in the JJA and MAM seasons. However, the four models, particularly the CSIRO model during the SON season, display different variations in rainfall. Each climate model exhibits distinct biases relative to observational data; however, these biases are significantly reduced through bias correction. Despite this improvement, residual differences between model outputs and observations contribute to uncertainty in projected rainfall variation. Therefore, assessing the probability of future rainfall remains essential.

Probability of Future Seasonal Rainfall Changes

To address the uncertainty of rainfall projection, it is essential to assess the probability of future rainfall conditions specifically, the likelihood of above-normal, near-normal, and below-normal rainfall. Such probabilistic information is critical for the sustainable management of Bintan Island's water resources, as rainfall is the primary determinant of water availability on the island.

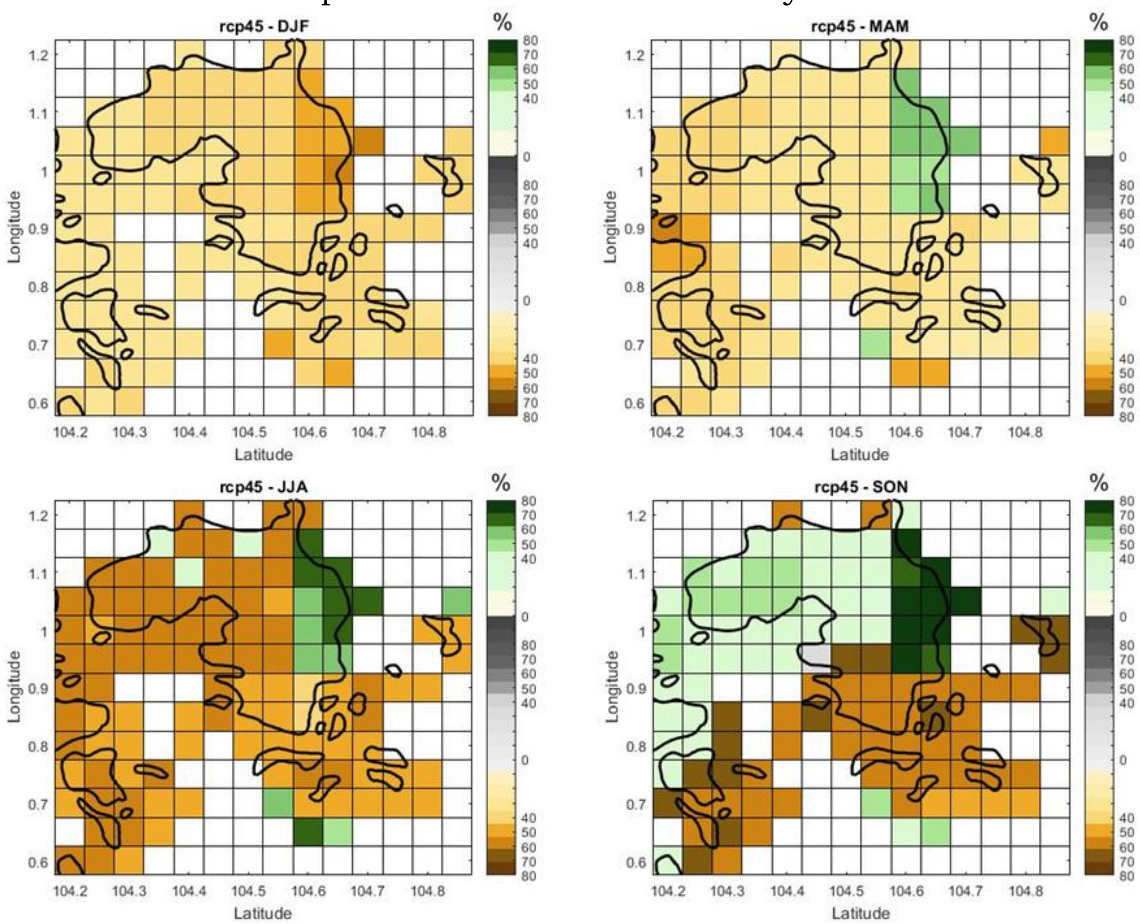


Figure 6. Probability of Future Seasonal Rainfall at Bintan Island

Figure 6 illustrates projected seasonal rainfall probabilities for Bintan Island based on outputs from four regional climate models under the RCP 4.5

scenario for the period 2006–2045. The analysis suggests that the island is likely to experience below-normal rainfall during the DJF (December–February) and MAM (March–May) seasons, with probabilities ranging from 27% to 54%. The JJA (June–August) season has the highest chance of below-normal rainfall with probabilities between 40% - 65%.

During the SON (September–November) season, the northern region of Bintan Island is projected to have a 40%–50% probability of above-normal rainfall, while the southern region is expected to experience a 43%–64% probability of below-normal rainfall. Densely populated areas in the western and southern parts of the island face approximately 50% probability of below-normal rainfall, indicating potential risks to water availability in key urban centers.

In contrast, the eastern region of Bintan Island is projected to experience above-normal rainfall during the MAM (March–May), JJA (June–August), and SON (September–November) seasons, suggesting lower vulnerability to seasonal water deficits. Overall, the projections indicate a high likelihood of below-normal rainfall across much of the island in the future, emphasizing the need for proactive and climate-resilient water resource management strategies.

DISCUSSION

Rainfall variability in Bintan Island is influenced by the Asia-Australia monsoon, synoptic atmospheric dynamics, ITCZ, ENSO, IOD, and MJO (Aldrian and Susanto, 2003; Narulita et al., 2021). The future rainfall projection study is important in this region because Bintan Island's water resources are very dependent on rainfall variability. The CORDEX-SEA climate model is the high-resolution climate projection data model currently available, which uses a daily temporal resolution and a 25 km spatial resolution. This spatial resolution is insufficient for research on small islands; therefore, bias correction is required to enhance the spatial resolution (Inomata, 2011)..

Downscaling using a bias correction method was carried out for Bintan Island, employing daily rainfall data from a single observation station located in Kijang. This station stands as the only ground rainfall observation station on the island, which, fortunately, provides a sufficiently long observational record that aligns with the temporal coverage of the CHIRPS rainfall dataset. Despite the use of a single-point dataset, the bias correction produced satisfactory outcomes, as evidenced by the resulting gridded climatology, which reflects a typical equatorial rainfall pattern (Narulita et al. 2021). The use of single-point bias correction is considered appropriate for Bintan Island because of its relatively small area approximately 1,173 km² and its predominantly uniform topography. Notably, about 85% of the island consists of lowland terrain with elevations between 0 and 50 meters (Figure 1.), which lower spatial variability in rainfall and supports the reliability of the correction approach.

All uncorrected CORDEX-SEA models (CNRM, CSIRO, EC-Earth, and MPI) generally underestimated the rainfall projection (Figure 2). The corrected CORDEX-SEA models perform line with observation data than the uncorrected ones, based on the CDF plots, The root mean squared error (RMSE), and the monthly climatology graph of rainfall over the Kijang station grid point (Figure 2). The four corrected CORDEX-SEA models (Figure 5) exhibit varying values for monthly rainfall (Figure 4), although they generally align with the CHIRPS data. This indicates that the CORDEX-SEA climate models contain some difference bias that led to uncertainty among the models (Tangang et al., 2019, 2020; Djuwansah et al., 2021; Phan-Van et al., 2022; Phuong Nguyen-Ngoc-Bich et al., 2022). These results highlight the significant uncertainty inherent in the CORDEX-SEA models, underscoring the necessity of using multi-model ensembles for more robust and reliable future rainfall projections (Tangang et al., 2020). The bias correction applied to the CORDEX-SEA data was intended to reduce systematic bias and enhance spatial resolution rather than to address model uncertainty (Figure 2 and 4 and Supplementary Information). By minimizing bias, the corrected CORDEX-SEA dataset provides a more reliable representation of the observed rainfall patterns. Plots of rainfall data from the four CORDEX-SEA models both before and after correction show considerable variability. However, the bias-corrected models exhibited improved consistency with the observational data, highlighting the effectiveness of the correction process in refining the model outputs (Figure 2).

Figure 5 shows the future changes in rainfall patterns over Bintan Island, highlighting the impacts of climate change on all four seasons. The bias correction procedure effectively reduces the systematic deviations between the modeled and observed precipitation without altering the uncertainty of the original model outputs (Figure 4. and Figure 5.) Because of the uncertainty of the corrected CORDEX-SEA data, it is important to take probabilistic approaches to improve the reliability and interpretability of future rainfall projections. Previous studies using uncorrected CORDEX-SEA data showed a slight increase in rainfall during the DJF (wet) season and a decrease during the JJA season around Bintan Island (Supari et al., 2020; Tangang et al., 2020). Similarly, a study by Kang (2019) showed that future rainfall during DJF is likely to increase in the region. The climate models used in these previous studies had spatial resolutions of 25 kilometers and 12 kilometers, respectively. In contrast, our findings suggest that almost the entire Bintan Island may experience below-normal rainfall in the future, with a probability of 27%–54% during the DJF and MAM seasons and 40%–65% during the JJA season, accompanied by spatial variations (Figure 6.). These findings highlight the need for high-resolution or more regionally detailed climate models when conducting climate impact assessments in small island regions. Nonetheless, our results are consistent with those of Tangang et al. (2020), who projected a 10%–30% reduction in rainfall over Indonesia during the JJA (June–August) season. In comparison, our analysis indicates a 50%–65% probability of below-normal rainfall across Bintan Island during the same season.

Additionally, while a slight probability of above-normal rainfall (approximately 40%–50%) is projected for the northern part of Bintan Island during the SON (September–November) season, the southern region shows a higher probability (43%–64%) of experiencing below-normal rainfall. These spatial variations underscore the importance of localized climate assessments in adaptive water resource planning. Future projections indicate the potential for belo-normall rainfall in the densely populated areas in the western and southern parts of Bintan Island; in contrast, the eastern part of the Island is expected to experience above-normal rainfall in the future. This spatial disparity in future rainfall highlights the importance of adaptive water resource management strategies. One approach is a strategically located rainwater storage reservoir in the eastern part, where rainfall is projected to increase. These reservoirs can help mitigate future water shortages by capturing excess rainfall and distributing it to water-scarce areas, particular during the dry season.

Since the geology of Bintan Island is predominantly composed of rocks exhibiting low to moderate permeability and having a limited capacity for groundwater storage (Kusmawa, 1994), most of the rainfall will flow as surface runoff and will quickly drain into the surrounding sea within a few hours. Under these geological and hydrological conditions, rainfall becomes the primary factor influencing the reservoir yield, playing a more significant role than other hydrological parameters in the selection of suitable reservoir sites. Further rainfall analysis shows that the eastern part of Bintan Island is projected to receive above-normal rainfall in the future. This region is therefore identified as a suitable area for developing water reservoirs. Establishing a reservoir in this region is essential to address potential water shortages in the future. Effective and adaptive water resource management strategies that incorporate the impact of climate change will be crucial for ensuring long-term water security on

Bintan Island, particularly considering potential future decreases in rainfall across other parts of the island.

4 CONCLUSIONS

The CORDEX-SEA climate model must experience correction before use in any processing or analysis, as the uncorrected outputs generally underestimate the observed values. In contrast, the corrected CORDEX-SEA data showed improved performance and greater reliability. Using the dataset, we calculated the probability of future seasonal rainfall on Bintan Island. Bias correction of the CORDEX-SEA data improves reliability by reducing bias and enhancing spatial resolution, not uncertainty. Rainfall plots from the four models show high variability across both the corrected and uncorrected data.

The projection indicates that Bintan Island is likely to experience a general decrease in rainfall during DJF (December-February), MAM (Marc-May), and JJA (June-August), with probability ranging from approximately 50%–65%, varying seasonally and spatially. The greatest probability of rainfall decrease occurs during the JJA season, where the probabilities reach up to 65%. During SON (Septeber-November) season, however, a spatial divergence is observed: the northern part of Bintan Island shows potential for above-normal rainfall, while the southern part is projected to experience below-normal rainfall conditions. The findings of this study offer valuable insights for policymakers in developing climate-resilient water resource management planning, including water resources conservation strategies and their location, particularly in small island settings vulnerable to climate variability and change.

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